PHD

The use of transmitter power control in land mobile radio systems

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Award date:
1987

Awarding institution:
University of Bath

THE USE OF TRANSMITTER POWER CONTROL IN LAND MOBILE RADIO SYSTEMS

submitted by

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for the degree of P.hD.

of the University of Bath

1987

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SUMMARY

The 'cellular concept' has been recognised as the most promising approach to mobile communications of the future. Its potential spectral efficiency is essential if the rapidly increasing demand for mobile radio service is to be met without requiring enormous allocations from the finite supply of suitable frequency reserves. Unfortunately, however, the problems of intermodulation and co-channel interference, which limit the communication ability and hence spectral efficiency of conventional mobile radio schemes, also threaten to do the same for cellular systems.

Many current cellular systems already employ mobile transmitter power control in order to help decrease the levels of intermodulation generated at base station sites through the use of aerial distribution amplifiers. However, as yet, such power control has not been extended to include base station transmitters and hence high levels of co-channel interference are being experienced in highly subscribed areas of such schemes.

This thesis investigates the contributions that a high grade base station transmitter power control system could make to the operational ability and overall

efficiency of narrowband FM land mobile radio systems. Consideration is given to the co-channel interference levels currently encountered in cellular type schemes, and the reduction in such interference afforded by the use of such a power control system. The aspects associated with the use of base station transmitter power control are also examined and the performance of such a system assessed through practical implementation and field trials.

The outcome of the research leads to the conclusions that a base station transmitter power control system could be implemented with a minimum amount of effort and could significantly alleviate the high levels of co-channel interference that are presently being experienced in well established cellular radio systems. Furthermore, the benefits obtained through the use of transmitter power control, both mobile and base station are applicable not only to cellular type systems but to all multi-channel mobile radio schemes.

ACKNOWLEDGEMENTS

The author would like to thank Dr. R.J. Holbeche for his assistance in the writing of this thesis.

The author is also grateful to Mr. I.W.J. Sparry for his help during the writing of the channel allocation software and in the final presentation of the thesis.

The author would also like to thank Racal-Vodafone Ltd. for their support during the preparation of this thesis.

CONTENTS

CHAPTER ONE

LAND MOBILE RADIO SYSTEMS

1.1 INTRODUCTION

Technical progress in the electronics industry over the past two decades has taken vast strides, with the land mobile radio (LMR) sector certainly not lagging behind. The growth of LMR services during these years reflects the importance of these services to all forms of industry. The ability to communicate with 'mobile' people either on a local or national scale enables industry to operate more effectively and efficiently. Further developments in LMR services have the potential to raise levels of industrial efficiency even higher but unfortunately are being stifled by the lack of available frequency spectrum.

The fact that LMR, in its broadest sense, was the first service to make use of the radio spectrum has never been reflected in the allocation of frequency spectrum. The modest allocations that have been made through the years have always been a cause for concern, and have led to a high level of system development in order to accommodate the growth within the service. Unfortunately, the stage has almost been reached where such tactics are no longer sufficient to cope with the increasing demand on mobile communications. Indeed, it has been suggested [1] that a state has now been reached whereby the growth of mobile communications is no longer technically led, but is under the control of the frequency spectrum legislators. Since future systems are dependent on their 'parents', the consequences of such spectral limitations could lead to severe restrictions of LMR services, with longstanding repercussions in many industries.

It has been suggested that the rapid growth of LMR services could not have been foreseen by anyone [2]. This fact tends to be borne out over the years by the predictions for user numbers falling well short of the actual figures achieved. It is believed that had the problems of spectrum availability not been present, such numbers could well have been even higher. From this point of view it is possible to understand why problems have arisen over the unavailablity of spectrum throughout the years. More recently, two new frequency bands have been opened up for use by LMR services. To ensure the future of mobile communications it is essential that systems operating in these bands be as spectrally efficient as possible.

This chapter contains a history of LMR in the UK from its conception it the late 19^{th} century to the present day by detailing some of the major changes that have occurred in the service. Consideration is also given to the growth of LMR services together with the corresponding increase in the number of users and the changing role of the mobile radio user. Finally the problems of spectrum congestion are discussed together with the methods that have been used in the past to maximise the spectral efficiency of LMR systems.

1.2 HISTORY OF MOBILE RADIO IN THE UK

The history of mobile communications can be traced back to the advent of radio in the late 1800's and the first experiments of the radio pioneers. The initial demonstration of practical radio communication by Hertz in the 1880's was closely followed in 1898 by the installation of one of the first mobile radio systems. The system, designed and developed by Marconi, was installed in the grounds of Osborne House in the Isle of Wight for use by Queen Victoria. It is believed to have operated mainly in the VHF band (30-300MHz) and was used for communicating with the Royal Yacht. However, at that time Marconi was more interested in communication over longer distances than the approximate line-of-sight range of such VHF systems, and so turned to transmission at lower frequencies.

During World War 1, radio communication achieved limited use, more out of curiosity than anything else. After the war mobile radio systems operating in the MF (300kHz-3MHz) and HF (3-30MHz) bands with amplitude modulation were installed for use by the police and fire services. In the late 1930's the neglected VHF and UHF (300-3000MHz) bands came back into use when trial systems operating first at about 30MHz and later at higher frequencies were installed for the police and fire services as an alternative to their noisy and interference prone MF and HF systems.

The Second World War brought about rapid developments in VHF communications for military use. The police and fire services also benefited from these developments, and by the end of the war many such services were using VHF AM equipment in the 80-130MHz band. Despite the initial demonstration back in 1935 of frequency modulation by Armstrong, its use was still only in the experimental stage in the UK, and hence was employed in relatively few systems.

1947 saw revised frequency allocations for mobile radio with specific modulation methods being laid down for specific frequency bands. Confirmation of these frequencies in the UK was followed by the issuing of the first private mobile radio licences to the Camtax taxi company in Cambridge, and to a tug firm operating on the Tyne and Wear rivers. The first wide area coverage scheme employing multiple transmitting and receiving sites was also commissioned in the same year.

A year later the first public radiotelephone system was installed by what was in those days, the British Post Office. Two 2-frequency AM channels allocated at the high end of the VHF band provided service to small vessels on the river Thames. The Post Office also considered setting up a countrywide network of stations to be used by LMR services in the private sector, but the rapid licensing of privately operated systems resulted in the plan not being implemented.

In October 1959 the Post Office, mirroring developments elsewhere, particularly in the United States and in other parts of Europe, introduced an experimental radiotelephone service in South Lancashire. The system offered for the first time in the UK, interconnection with the public switched telephone network. This was achieved by using a dedicated operator for the system who manually connected the radio channel into the normal telephone network. In the years that followed the service attracted little real attention and only a small minority of people were both willing and able to afford the cost. The limited technology of the day also made the system inefficient and inconvenient to use. Nevertheless, a modest level of development continued and the service, known as 'System 1', was eventually introduced in London in 1965, and in due course spread to cover other major areas of population.

In 1972 'System 3' was introduced by the Post Office and brought with it the technology of the day

('System 2' was never put into public service). It operated in the 155-169MHz frequency band and the 55 channels allocated to it allowed more users to be connected to it than the previous 9 channel System 1. However, it was still rather primitive in that all calls were handled by an operator and it still employed the 'press-to-talk' feature. Nevertheless, the system was eventually extended until it covered around 40-45% of the population, and continued service up to 1986.

General developments in telecommunications brought fully automatic radiotelephone systems by the mid 1970's. In July 1981 the Post Office installed the first automatic system to the UK in the London area. The system, known as 'System 4', operated in the same band as System 3 and offered the user the feature of direct dialling. It also did away with the press-to-talk requirement thus making the operation more 'telephone-like'.

January 1985 saw the start of a new kind of radiotelephone service in the UK. The system, based on the cellular concept of small service areas and large scale re-use of channel frequencies, offers the features necessary to take LMR into the 21st century. By 1990 this service should be available to the majority of the UK population, not only in terms of coverage but also in cost, and will make it the first national telephone network of its type in the world.

1.3 GROWTH OF MOBILE RADIO SYSTEMS

The use of mobile radio communication systems has been historically characterised by the two significant criteria of mobility and urgency. Back in the 1900's nothing was more 'mobile' than a ship at sea, nor more 'urgent' than a sinking ship. Thus the first major use for mobile radio schemes was communications to vessels at sea. In the same way on land, after the introduction of cars into the police force, nothing was more 'mobile' than a police car, nor more 'urgent' than an accident or crime in progress. The fire service was the next obvious candidate for a mobile communication system and was followed by the installation of schemes for other public utilities ie. the electricity industry, etc. Private companies began to realise the advantages of having communications to their mobile employees and soon started having systems installed.

Since those early days of mobile communications, the number of users and the variety of uses of such systems have increased dramatically. The rate at which mobile services have grown throughout the years has served to illustrate the importance placed on these systems. The background of mobile communications has generally been one of continuous growth interspersed with periods of explosive growth. The user characteristics of mobility and urgency have now been joined by those of 'improved work efficiency' and 'cost effectiveness'. Technological advances have also broadened the market for mobile radio schemes by making available a wider range of facilities and services.

Since the 1940's, the number of mobile radio users has been increasing at an exponential rate. This is illustrated in Figure 1.1 which shows the growth in users between the years 1950 and 1980 derived from the official statistics of the licensing authorities. However, the sales records of the equipment manufacturers tend to suggest that these figures are in fact pessimistic, and that there are many more users operating without a licence. Up to 1970, the rate of growth had remained steady at approximately 15% per annum for many years [3]. Between 1970 and 1975 the figure slowly fell to 10% [3] due mainly, it is thought to the recession. Since then the rate of growth has gradually been increasing and in 1985 was running at around 12% [4]. Latest statistics available show that at present there are some 17,000 different users of mobile radio systems, having in excess of 20,000 base stations and more than 350,000 mobiles [5]. An indication of how these users are distributed can be obtained from Table 1.1 which shows the situation as it was back in 1980 [6].

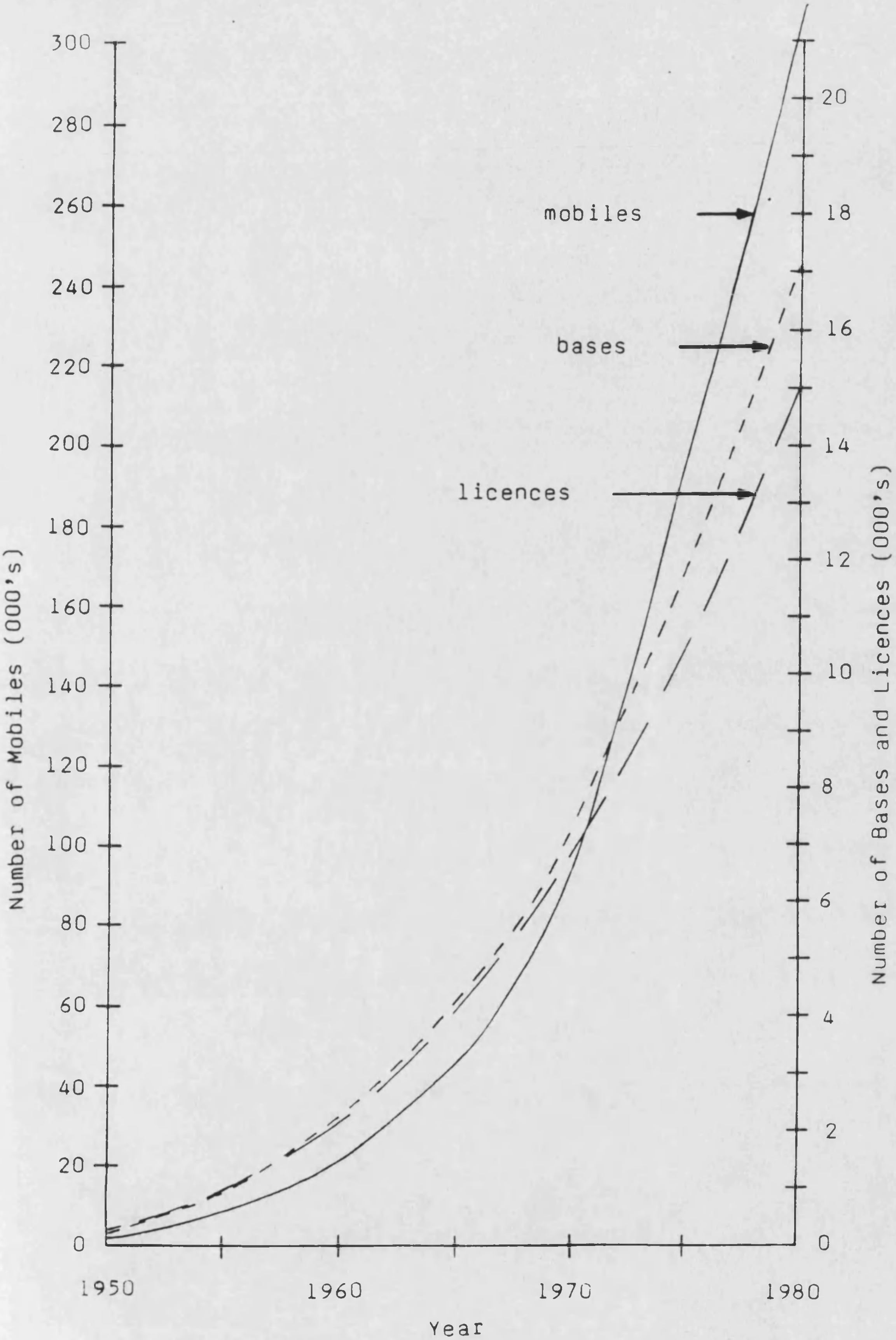

Figure 1.1. Growth of Mobile Radio Services in the UK.

Category	Number of Mobiles
Central Government	5700
Local Government	29900
Manufacturing/ Commercial	99540
Services	39231
Public Transport	19200
Other Transport	55414
Utilities (excluding Royal Mail)	59249
TOTAL	308234

Table 1.1. Distribution of Mobiles in the LMR Service.

The recent awareness of the limit to, and real cost, of traditional energy sources has generated a surge in mobile communications, particularly in the industrial and commercial world. Reliable communications with the estimated 30% of the workforce that is mobile for part or all of the day [4], allows industry to operate with greater efficiency and in some cases forms a backbone, without which some companies would collapse. A saving of between 10 and 20% is often quoted as a figure effected by the use of a mobile radio system in the running costs of a transport company [3]. It has further been suggested that a 1% reduction in the distance covered by the UK fleet of vehicles could produce an annual saving well in excess of £ 80 million [7].

The introduction of a radiotelephone network back in 1959, thus allowing mobile radio users to be connected into the public switched telephone network, opened up the use of mobile communications on an individualistic basis. The application of transistors in the early 1960's and the introduction of integrated circuits in the 1970's enabled the 'black box' image of mobile radio equipment to be removed. Transistors permitted really low power consumption portable sets to be designed for the first time, the demand for which was illustrated by the spectacular sales figures of such sets in their early years. The use of integrated circuits brought about a further reduction in size and improved the reliability of the equipment.

With the introduction of a countrywide cellular mobile radiotelephone system, the demand for mobile radio units can only increase, and it is suggested that this increase could be at a very rapid rate. By the end of 1990 predictions are that there will be in excess of 700,000 mobiles in the UK and possibly over 2 million by the end of the century [5].

1.4 SPECTRUM CONGESTION

Ever since the advent of mobile radio communications, LMR has suffered from a lack of available frequency spectrum. The prolific increase in users over the years has not been accompanied by the corresponding increase in new frequency allocations, and as a consequence LMR has had a constant battle to improve spectrum efficiency in order to accommodate its users. Most of this increased spectrum efficiency has resulted from a reduction in channel spacing. The very early systems used channel spacings of 180-200kHz, but these had been gradually reduced to 100kHz by the start of the 1950's. At the International Radio Conference (IRC) of 1947 mobile radio frequency bands were revised, resulting in a mere 4.7% of the then available spectrum being allocated to such services. This was by no means sufficient to support existing mobile radio systems, let alone cope with the growth that the service was experiencing. Concern about the shortage of channels and the requirement to continue increasing the spectrum efficiency of mobile services was resolved by another reduction in channel spacings to 50kHz. Since then, more pressure on the allocated spectrum has brought about further reductions of channel spacings. The current situation in the UK is for 12.5kHz channel spacing in the VHF bands and

25kHz channel spacing in the UHF bands. Acting on the advice of the Mobile Radio Committee (MRC), each reduction in channel spacing from 50kHz downwards has been accomplished by halving the spacing of existing channels and inserting new channels centred at the edge of the old ones. This provided a substantial increase in the number of available channels whilst still retaining the possibility of continued operation of older equipment in the original channels if the level of interference was sufficiently low.

Further increases in spectral efficiency could be brought about by another halving of channel spacings. A proposal to halve the 25kHz channels in the 420-470MHz UHF band was rejected in 1972 because of the inadequate frequency stability of the equipment then available. This however, is no longer the case and active progress is being made towards the introduction of 12.5kHz spacing in this band. Initial tests have also been carried out on 6.25kHz spacing in the VHF bands, and have shown that such a reduction is possible [8]. Any further reduction in channel spacing would however, mean a change in modulation methods from AM and FM to SSB. Whilst SSB and 4-5kHz channel spacing has been shown theoretically to be feasible for LMR [9],[10], its introduction would cause incompatibility with existing equipment, and could also prove to be detrimental to the use of digital techniques within the service.

Unfortunately, the successive reduction in channel spacing brought with it numerous problems. The number of possible intermodulation products increased by a factor of seven to eight for third order products with every halving of the channels [11]. However, careful frequency planning helped to reduce this problem and enabled the new systems to operate satisfactorily. A further problem resulting from the reduction was that of increased adjacent channel interference. Advances in filter technology made it possible to increase the selectivity of mobile receivers thus reducing levels of adjacent channel interference. Increases in oscillator stability also helped to improve the adjacent channel interference performance by maintaining transmitter outputs more closely to their nominal frequency.

As channel spacings became smaller, corresponding reductions in channel bandwidths were introduced. In doing so, the adverse effects of such reductions on the performance of systems using FM increased whilst with AM systems the degradation in performance was considerably less. Capture effect and its advantages had long been the theme of the argument in support of using FM rather than AM. This capture effect enabled the geographical separation necessary between two systems operating on the same frequency to be reduced in comparison to AM systems, and hence increased the spectrum efficiency. Unfortunately, the propagation characteristics of the mobile radio channel together with the present channel bandwidths mean that this capture effect has now all but disappeared [12].

Back in the late 1970's the major frequency bands available to LMR systems were as shown in Table 1.2. The VHF bands supported both FM and AM systems, with the latter being more predominant, whereas the UHF band was totally FM systems. In 1979, the World Administrative Radio Conference (WARC) took place in Geneva to plan the use of the radio spectrum up to the year 2000. The major changes relating to LMR systems were

(1) LMR schemes must vacate broadcast band II (from 87.5-104MHz by 1989 and from 104-108MHz by 1995).

(2) LMR is added as a permitted service in television bands I (41-68MHz) and III (174-230MHz).

(3) LMR is added as a primary service in the UHF television band from 860-960MHz.

The removal of LMR from broadcast band II was not totally unexpected, but was to occur sooner than was

Designation	Band (MHz)	
	From	To
Low Band	71.5	88
Police and Fire Bands	80	85
	97	102
Mid Band	105	108
	136	141
High Band	165	174
UHF Band	425	470

Table 1.2. Nominal Frequency Bands Available to LMR Services.

hoped, and would put even more pressure on the already crowded frequency allocations. The opening of television bands I and III to LMR as a permitted service helped offset this problem, but at that time they were very heavily loaded in Western Europe, and it appeared that LMR use would be available only to a very limited extent. However, the decision by the Government to close down the 405-line television system in the UK by the end of 1984 meant that the use of bands I and III by LMR would be more extensive than at first thought, offering a welcome expansion for mobile communications. Although it has now been decided that band III is to be used exclusively for mobile services in the UK, neighbouring countries are to continue with television broadcasting in these bands, at least for the time being. Thus plans have had to be drawn up to enable both services to operate satisfactorily in the presence of the other.

The 860-960MHz band is ideal for short range mobile communications and has been put to use in such a way. 50MHz of the band has been allocated by the UK Government to a cellular mobile radiotelephone system, bringing much needed relief for the demand for such equipment, especially in London. The potential 1000 channels made available will go a long way to solving the present problems of spectral overcrowding. Although the number of channels may sound impressive, the fact is that even at the present rate of growth of mobile services, the future rate being expected to be much faster, the spectrum could well be cluttered again in about 30 years. However, it is agreed that the use of the cellular concept is the best way of ensuring that the system operates to a high degree of spectrum efficiency, and hence prevent the inevitable problems of spectrum congestion reappearing any earlier than is absolutely necessary.

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CHAPTER TWO

CELLULAR LAND MOBILE RADIO SYSTEMS

2.1 INTRODUCTION

The provision of adequate spectrum to meet the continually increasing demand for mobile radio licences is a problem that has faced national administrations for many years. Successive reductions in channel spacing, together with the use of digital signalling techniques and frequency sharing schemes have helped ease the situation, but can clearly not continue indefinitely and other solutions must be sought.

Back in the late 1970's LMR was in desperate need for new frequency allocations to be made available. This was particularly the case in the mobile telephony service. For many years mobile telephony had been the poor relation of the main telephone network. In the UK there were approaching 15 million main telephone subscriber lines, in contrast to the 5,000 mobile telephone subscribers, the majority of which were in London [1]. This was mainly due to the limited spectrum available to the service rather than the lack of demand, since when additional capacity had been added to the service the number of users had risen very rapidly to fill the new capacity and the length of the waiting list had remained approximately constant.

At the WARC conference in 1979 much needed relief was brought to the mobile radio world by the allocation of 100MHz of spectrum around 900MHz. For the future of mobile communications it was of the utmost importance that this band be used by systems offering the highest degree of spectrum efficiency. In 1982 the UK Government allocated 50MHz of this band to be used for a mobile radiotelephone service. In order to achieve the necessary high level of spectral efficiency the system was to be based on what has come to be known as 'the cellular concept'.

This chapter details the history and development of the cellular concept and its application to LMR systems. Although many countries have been involved in the research and development of cellular mobile radiotelephone schemes, concentration has been centred on the work carried out by Bell Telephone Laboratories (BTL), USA on their Advanced Mobile Phone Service (AMPS) due to its direct relevance to the UK cellular system. The basic elements of the cellular concept are discussed, together with the advantages that they possess in enabling a large capacity highly spectral efficient mobile service to be provided.

2.2 THE HISTORY OF CELLULAR LAND MOBILE RADIO

The realisation that the application of the cellular concept to LMR systems could result in a dramatic increase in the user capacity of such systems seem to have materialised from nowhere. However, such an idea it is claimed [2] was voiced in 1947 by D.H.Ring of BTL in one of his unpublished articles.

It was as far back as 1946 that system planners at the BTL started looking forward to the large scale high capacity mobile telephone service (HCMTS) they believed would be necessary to satisfy customer demands of the future. The first concept to be appreciated as a requirement for this efficient large capacity system was 'trunking'. Trunking is the ability to combine several radio channels into a single group so that a mobile can be connected to any unused channel in the group. This arrangement greatly increases the efficiency of a system relative to the situation in which a mobile can only use one fixed channel. However, to obtain the maximum benefit from trunking, each mobile unit would be required to have the ability to tune to every channel in use on the system throughout the entire coverage area. In those days, each operating frequency meant two quartz crystals and a position on the channel selector switch. Since the system would be using many 10's of channels this posed a problem which at the time the planners could not see how to overcome. The solution to the problem was the frequency synthesiser, which although the basic idea existed, only became practically and economically feasible in the early 1970's.

Over the next 20 years much time and effort was devoted by the planners to the design and development of such a system. During this time several proposals were put forward to the Federal Communications Commission (FCC) regarding the possible implementation and spectrum requirement of this type of system [2]. It was in this period that the cellular concept began to be formalised.

In 1968 the FCC found themselves under considerable pressure to provide more spectrum for mobile radio communication systems. In 1970 they tentatively decided to make a total of 115MHz available for such systems, 75MHz of which would be allocated to a new high capacity mobile radiotelephone scheme. The FCC invited industry to submit proposals for achieving this communication objective and demonstrating feasibility. The people at BTL responded in 1971 with a technical report which asserted feasibility by showing in considerable detail how such a system might be composed.

In 1974 the FCC made a firm frequency allocation of only 40MHz instead of the 75MHz which they had originally announced, and requested applications for developmental cellular systems to prove feasibility. The spectrum was situated in two bands, 825-845MHz for transmission from mobiles, and 870-890MHZ for transmission from base stations. In July 1975 the Bell Telephone Company of Illinois filed a request to the FCC for authorisation to install and test a developmental system in Chicago. This request was granted in March 1977, and a trial service began in December 1978. The system, which was known as the Advanced Mobile Phone Service (AMPS), had been designed with the following objectives in mind.

(1) The capability to serve a large number of users within a local service area, with a fixed allocation of radio channels.

(2) A highly efficient use of radio frequency spectrum so as to be able to cope with the anticipated large volume of customers within the allocated band.

(3) Adaptability to varying user densities due to the non-uniform geographical population distribution and the variations in this with time.

(4) The ability to adapt to use by hand portables without requiring changes in network design.

(5) Nationwide compatibility enabling a subscriber to achieve satisfactory service through any such system wherever they may be.

(6) The widespread availability of a mobile system such that users may be far from their normal home system and still receive service.

(7) The quality of the service should be as near as practically possible the same as that provided by the standard land telephone system.

(8) In addition to all the regular telephone services, it should provide specialised services and features which are particularly valuable in a mobile environment ie. dialling a number before picking up the handset, etc.

(9) The service should be affordable by a substantial portion of the public and businesses.

Since the successful installation and trial of this first cellular mobile radio service such systems have spread rapidly across the USA. By the end of 1984 nearly two dozen cities were served by a cellular mobile system with a total of approximately 40,000 subscribers spread across the country [3]. A further twenty systems were in the process of being installed, with many more being planned.

In Japan a cellular mobile telephone system has been in operation in Tokyo since early 1979, and by the end of 1984 six other major cities had systems installed.

Cellular mobile systems spread to Europe in 1981 with the installation of the Nordic Mobile Telephone (NMT) system in the four Scandinavian countries. Other European countries have, to a certain extent, lagged behind in the development and the commercial exploitation of cellular systems. However, most have now decided on the system that they will install, and should have coverage by the start of the 1990's, when it is reckoned over one million Western Europeans will subscribe to cellular radio services [4].

Due to the staggering of decisions by the various European countries as to the exact cellular system they will employ, there will be a lack of operational compatibility between systems in the different countries. This means that it will not be possible to make calls in other European countries using another countries mobile equipment. However, a second generation Pan-

European service is already being considered which will make this possible, the specification for which it is hoped, will be reached by 1988.

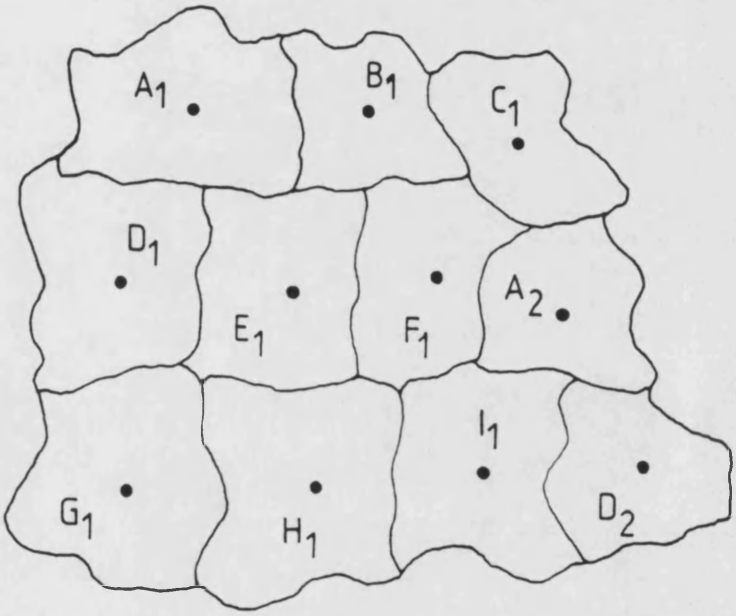
2.3 BASIC ELEMENTS OF THE CELLULAR CONCEPT

The basic elements of the cellular concept can be summarised by the two phrases 'frequency re-use' and 'cell splitting'.

2.3.1 Frequency Re-use

Frequency re-use is the name given to the use of radio channels to cover different areas which are geographically separated from one another by sufficient distances such that co-channel interference is not objectionable. This technique is employed to various extents in most radio services, however, the idea of employing frequency re-use in a mobile radio service on a reduced geographical scale leads to the cellular concept.

The concept of cellular mobile radio is that of dividing the total coverage area of a system into discrete interlocking regions, usually referred to as cells. Figure 2.1 shows an example of a possible cellular layout for a given service area. Within each cell is located a base station through which all communications with users in the cell are directed. In principle, the location and spacing of these base station sites need not be regular, and the cells need not be of any particular shape, however it will be shown later



Q_i — i^{th} Cell Using Channel Set Q

• — Transmitter Location

Figure 2.1. Cellular Layout Illustrating Frequency Re-use.

that an orderly geometrical structure to this cell pattern is advantageous.

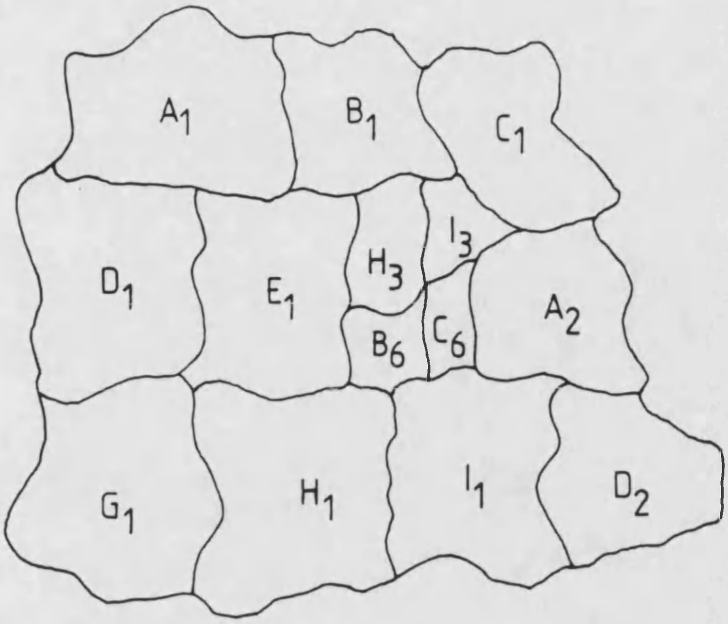
Each base station has radio and associated control equipment for transmission to and reception from any subscriber situated within the cell. A distinct set of channel frequencies is assigned to each cell so as to avoid co-channel interference problems. This is shown in Figure 2.1 by letters representing the different channel sets. Since base stations only communicate with users within their particular cell, and vice-versa, relatively low power transmissions can be used. This results in signals from a given cell being detectable over much shorter distances than in conventional mobile radio systems. Thus cells which are relatively close can have sufficient geographical separation to allow the use of identical radio channels in both cells without causing co-channel interference problems. This is illustrated in Figure 2.1 where A_1 and A_2, together with D_1 and D_2 are far enough apart to permit them to use the same channel set. It is through this high scale of frequency re-use that large coverage areas can be served with only relatively few channels enabling the system to achieve a high spectral efficiency.

2.3.2 Cell Splitting

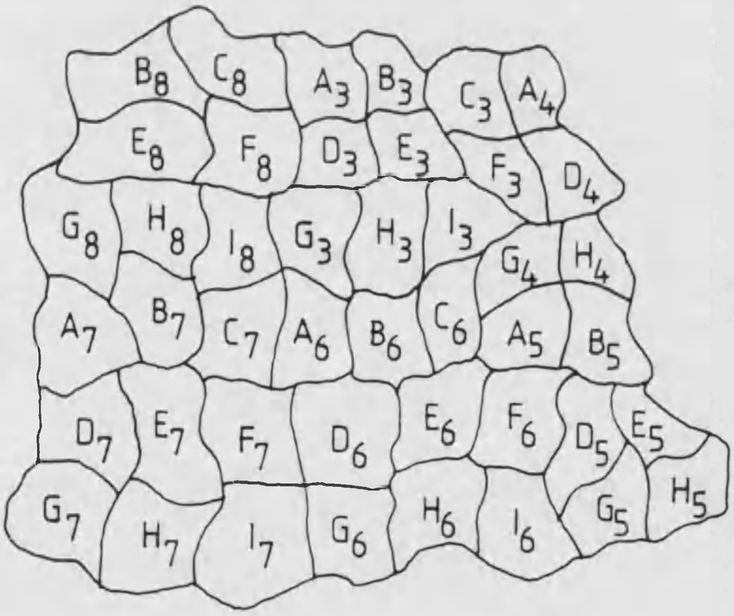
A second important feature of a cellular radio system is the ease with which it can grow to serve an increasing number of users. This is achieved through a process which is known as 'cell splitting', which can best be described by considering an example. If a cellular system is allocated a total of C radio channels, then partitioning into N channel sets will mean that each set will nominally contain S channels, where S is given by

$$S = \frac{C}{N} \tag{2.1}$$

Considering the system of Figure 2.1, although the system has a total of 10 cells only 8 cells have different channel sets due to frequency re-use. Thus, each cell will nominally have C/8 channels. As the number of subscribers on the system increases a point is reached where some cells will find that their S radio channels are no longer sufficient to support service to the large number of users within their coverage area. When this stage is reached the cell area can be split into two or more cells, hence the term 'cell splitting', and utilise all these cells' channels. Figure 2.2a shows a possible first cell split of the theoretical system of Figure 2.1. The cell which originally was shown as F_1



(a)



(b)

Q_i — i^{th} Cell Using Channel Set Q

Figure 2.2. Cellular Layout Illustrating Cell Splitting.

(a) Early Stage (b) Later Stage

has been split such that it now contains a total of four cells, namely H_3, I_3, B_6, and C_6. Frequency re-use is used for the new cells in the cell split, resulting in an increase in the communication capacity of the original cell without any further allocation of channels to the system. In this particular example, cell F_1 has a fourfold increase in user capacity. This cell splitting procedure can continue as demand within the system grows, Figure 2.2b shows a later stage in the cell splitting of the system of Figure 2.1. Theoretically the process can be repeated indefinitely, but obviously a point is reached where the cell area is getting too small to be practically viable. Cell splitting thus helps overcome the problem of matching the spatial density of available channels to the spatial density of demand for channels.

Cell splitting together with large scale frequency re-use permit a cellular system to meet the important objectives of serving a very large number of users whilst using a relatively small portion of the frequency spectrum. It is this ability that has made a cellular mobile radio system so attractive for future mobile schemes.

2.4 THE GEOMETRY OF THE CELLULAR CONCEPT

The main purpose of defining cells in a mobile radio system is to delineate areas in which specific radio channels will be used. This degree of geographical confinement of channel usage is essential if co-channel interference is to be kept to acceptable levels. Due to the propagation characteristics of the mobile radio channel it is not possible to define these cells with any degree of precision in the sense that a cell will always serve mobiles within an area and never serve mobiles outside that area. Nevertheless, the concept of a cell remains valid in the context that it is an area in which a certain base station is more likely to serve a mobile than any other cell. On this basis, cells are more likely to be amorphous in shape. However, the absence of an orderly geometrical structure in the cellular pattern causes problems with system design and generally leads to system inefficiences. Visualising all cells as having the same shape helps prevent these problems arising by systemising the design and layout of a cellular system.

In previous mobile radio systems base stations have had mostly omni-directional transmitting antennas resulting in roughly circular coverage areas. However, for cellular design purposes the circle is an impractical shape for a cell due to the ambiguous overlaps or gaps produced by an array. On the other hand, the shape of a circle can be approximated by any regular polygon. The equilateral triangle, the square and the regular hexagon are the only regular polygons that can cover a planar region with no gaps or overlaps. Any one of these three polygons could be used as a basis for a cellular system pattern. However, the regular hexagon has an advantage over the other two in that for a given centre-to-vertex distance, the regular hexagon has a substantially larger area. Consequently for coverage of a given area, a layout composed of hexagons requires fewer cells and hence fewer base stations. A cellular system based on hexagons is therefore more economic to install and maintain than one with triangular or square cells, all other factors being equal, and so is more often than not chosen.

It has already been mentioned previously in this chapter that one of the essential features of a cellular mobile radio system is that of frequency re-use on a small geographical scale. When considering the layout of such a scheme, it is necessary to determine which set of channel frequencies should be assigned to each cell, and also the distance between cells with the same channel set. In performing this assignment a useful parameter to consider is the 'co-channel re-use ratio'. This is defined as the ratio of the distance between the centres of nearest neighbouring co-channel cells, D, to the centre-to-vertex distance, usually termed as radius, of the hexagonal cells, R. This ratio has been shown [5] to be given by

$$\frac{D}{R} = \sqrt{3N} \tag{2.2}$$

where N, as before, is the total number of unique channel sets in the system.

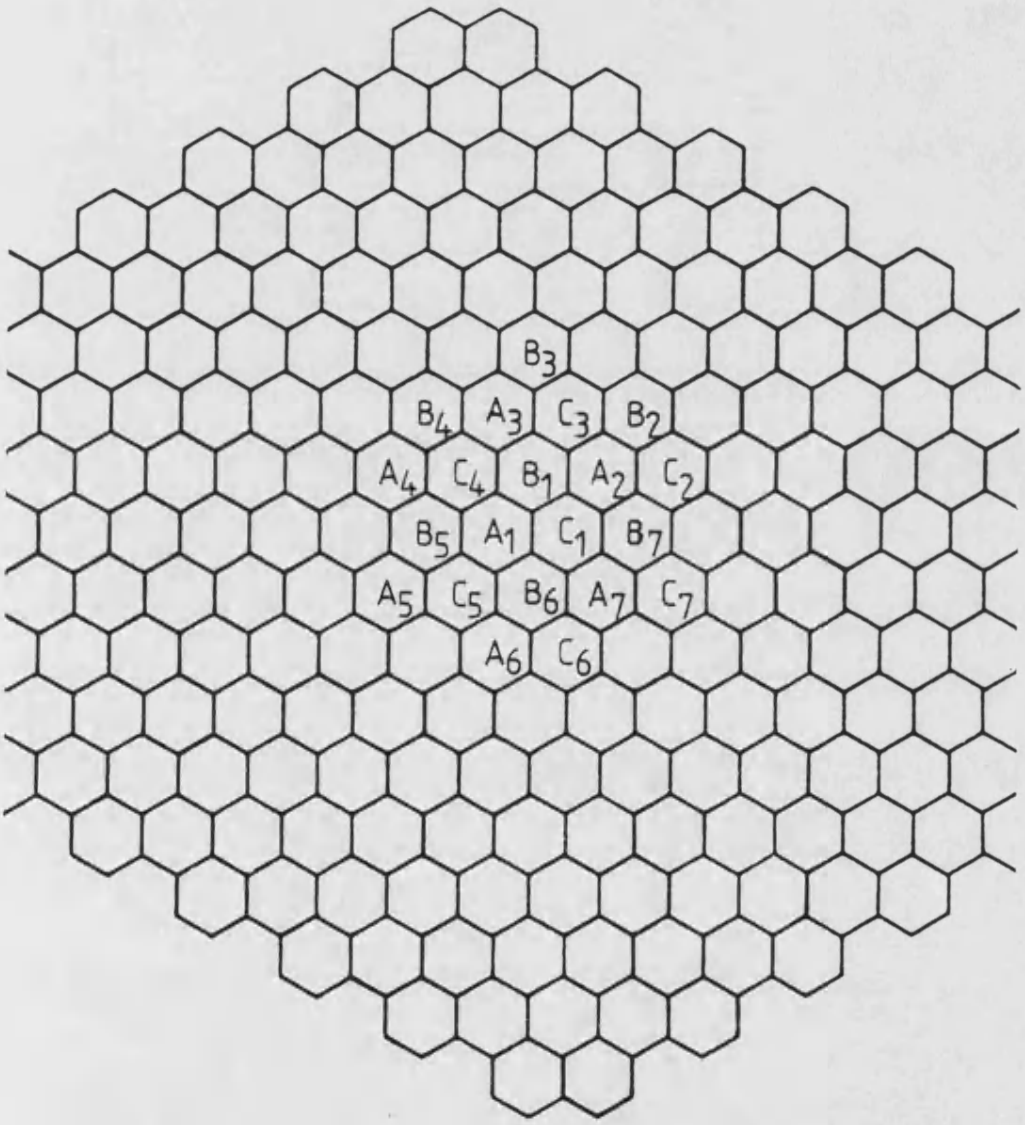
The cells tend to form themselves into a natural block or cluster of N cells, which is then repeated throughout the entire coverage area. The value of N, as might well be expected, must satisfy certain mathematical conditions guaranteeing that repetition of the cluster tessellates the whole service area. This has been shown to be the case [5] if

$$N = i^2 + ij + j^2 \tag{2.3}$$

where i and j are positive integers including zero.

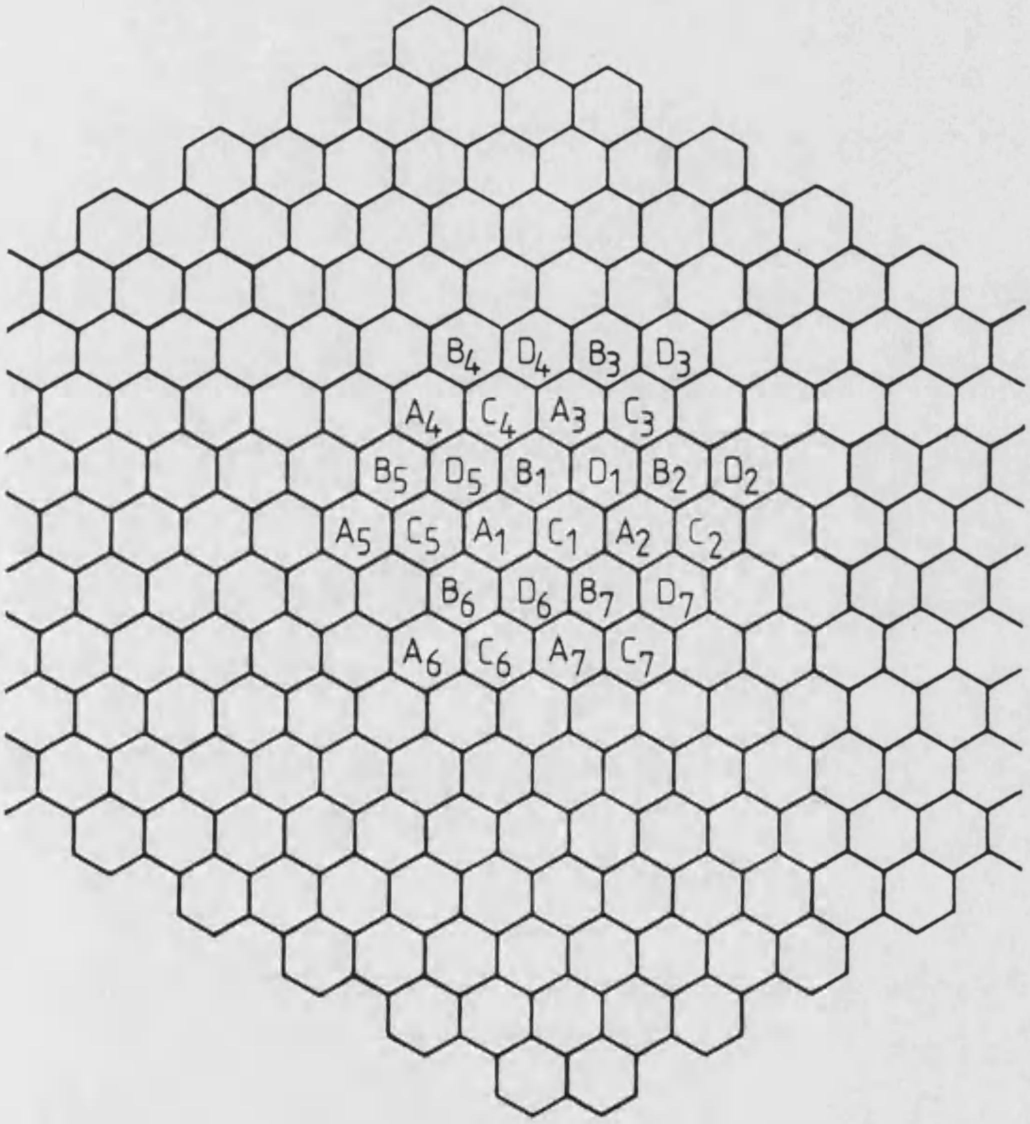
The exact shape of a valid cluster is not unique. All that is required is that the cluster must contain all the channel frequencies allocated to the system once and only once. Figures 2.3 to 2.7 demonstrate some of the possible cluster sizes and configurations.

It can be seen from equation 2.1 and Figures 2.3 to 2.7 that as the number of cells per cluster increases, then the separation between co-channel cells also increases. To avoid high levels of co-channel interference N must be large. Since the system is allocated only a limited number of channels, increasing N to reduce the levels of co-channel interference decreases the number of channels available to each cell. In order to prevent the call handling capacity decreasing at the same time, cell sizes must be reduced. This, however results in a requirement for more cells to cover the total service area and hence an increase in system cost. Thus, the choice of the number of cells per cluster must be given careful consideration.



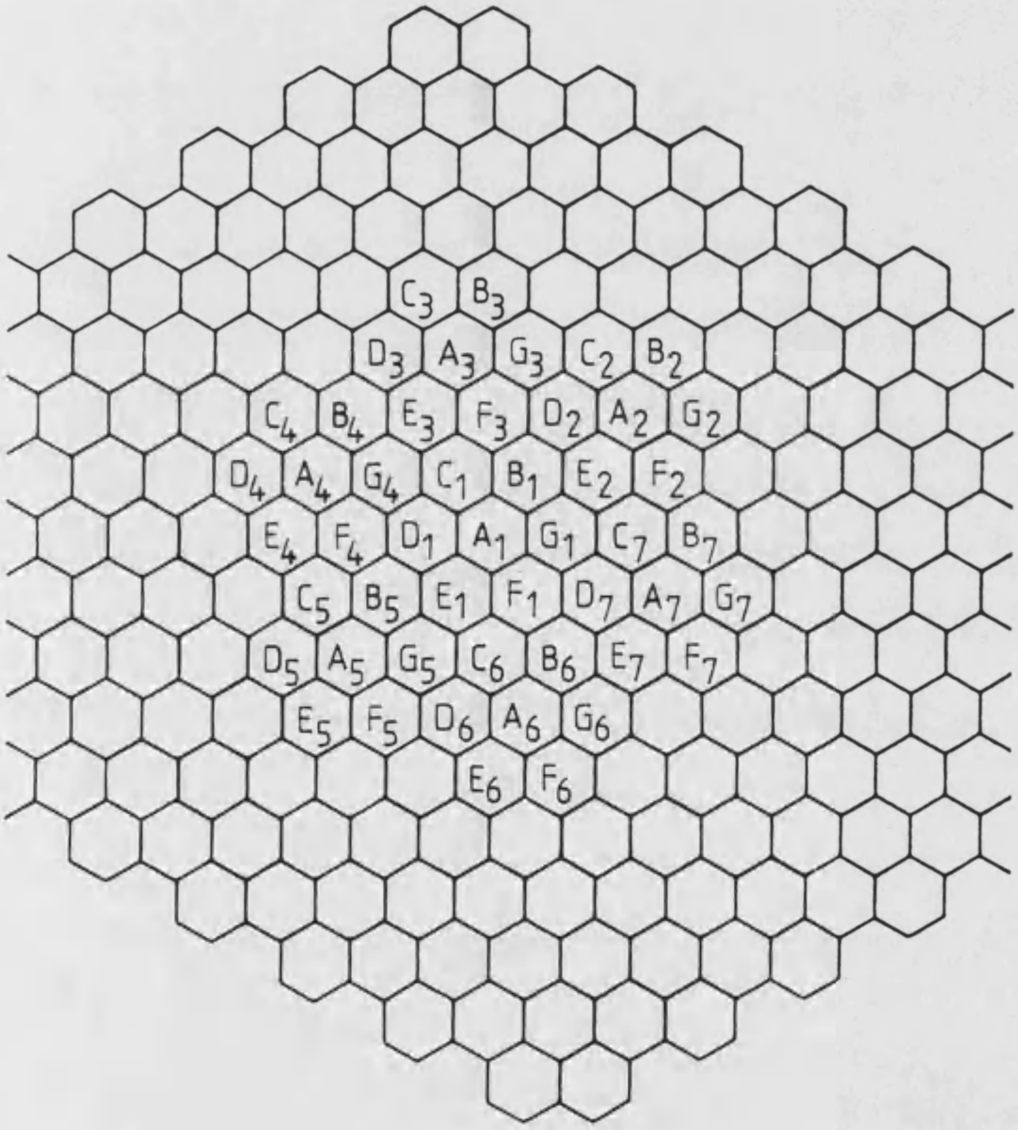
Q_i — i^{th} Cell Using Channel Set Q

Figure 2.3. Layout and Channel Set Deployment Pattern for 3 Cells per Cluster.



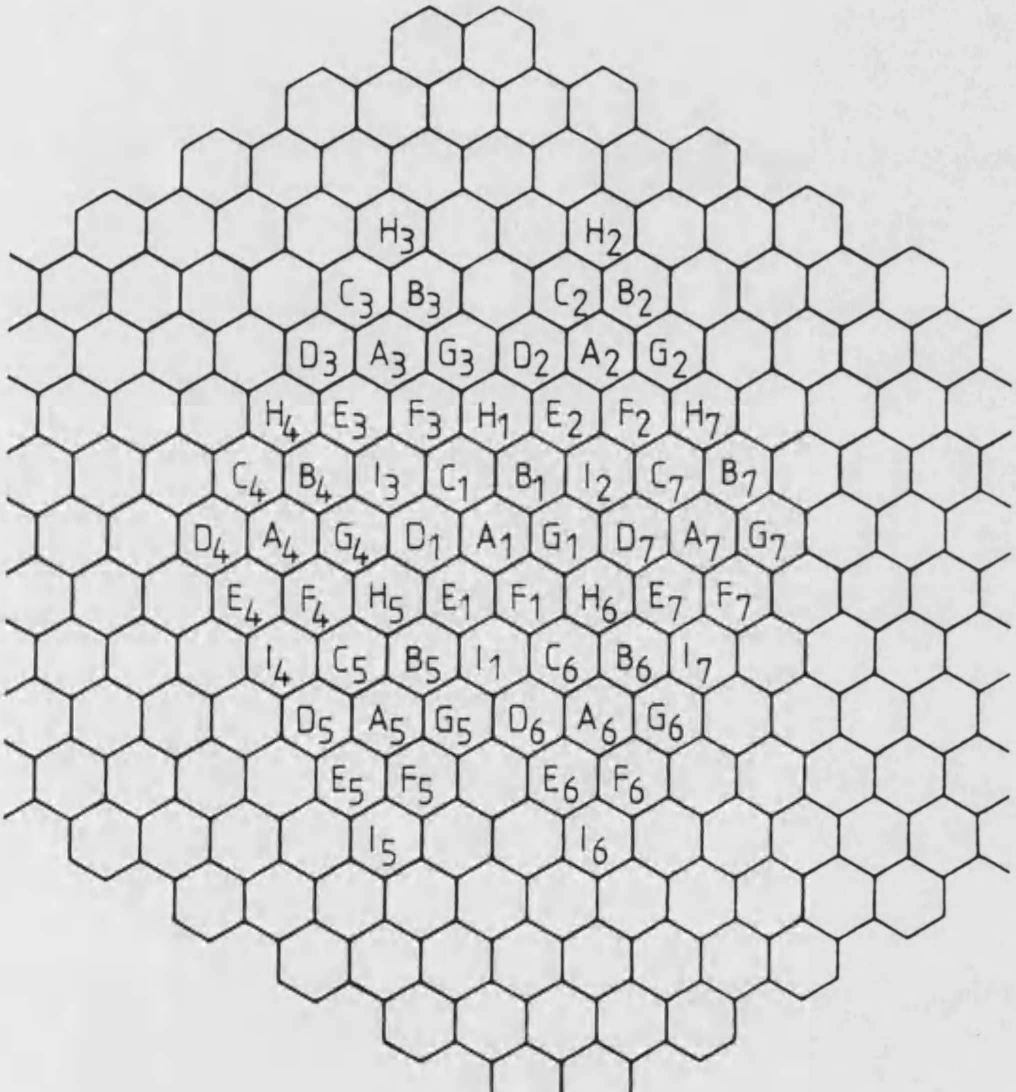
Q_i — i^{th} Cell Using Channel Set Q

Figure 2.4. Layout and Channel Set Deployment Pattern for 4 Cells per Cluster.



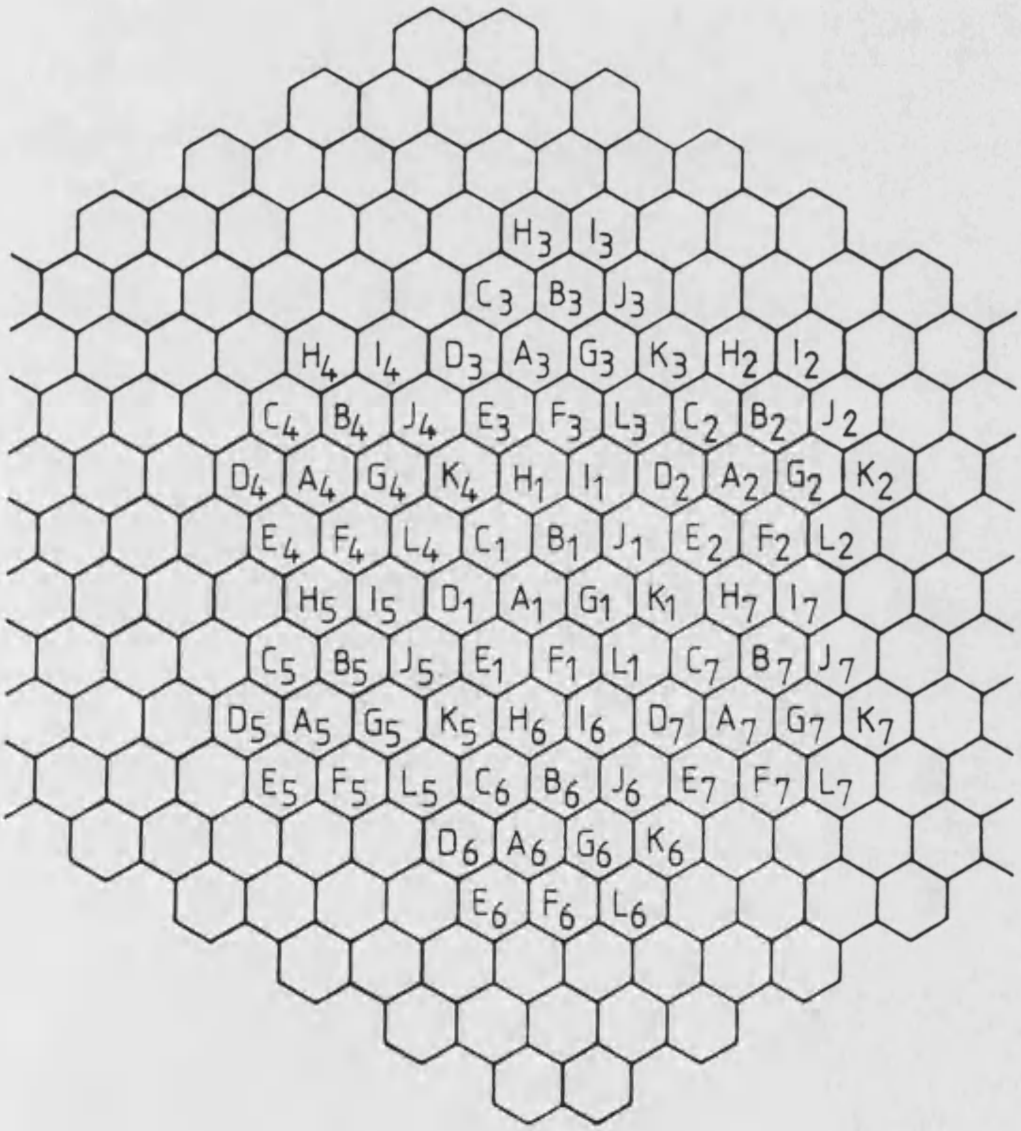
Q_i — i^{th} Cell Using Channel Set Q

Figure 2.5. Layout and Channel Set Deployment Pattern for 7 Cells per Cluster.



Q_i — i^{th} Cell Using Channel Set Q

Figure 2.6. Layout and Channel Set Deployment Pattern for 9 Cells per Cluster.



Q_i — i^{th} Cell Using Channel Set Q

Figure 2.7. Layout and Channel Set Deployment Pattern for 12 Cells per Cluster.

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CHAPTER THREE

PRACTICAL ASPECTS OF CELLULAR SYSTEM IMPLEMENTATION

3.1 INTRODUCTION

The cellular mobile radio system concept has been recognised as the most promising approach to mobile communications of the future. Perhaps the greatest virtue of a cellular system is its ability to handle a number of simultaneous calls which greatly exceeds the total number of allocated radio channels. This sort of spectral efficiency is essential if the rapidly increasing demand for mobile services is to be met without requiring enormous allocations from the dwindling suitable frequency reserves.

Over the past 3 to 4 years, interest in mobile communications in this country has been rekindled by the sudden UK moves towards implementing a cellular mobile radiotelephone network. Before the advent of such a system there were many more potential users of the mobile telephone service than the capacity of the network could cope with. However, this should no longer be the case and the number of mobile telephone users should rise dramatically.

It has always been clear that while the system concept was simple, the practical implementation of a cellular system would be far from it. In fact the means of implementing a multi-cell system only became possible with the advent of electronic switching technology in the early 1960's. Moreover, the necessary spectrum suitably spaced for duplex operation has only recently become available.

This chapter describes the operation of a typical cellular mobile radio system, and considers some of the aspects associated with the practical realisation of such a scheme. The background behind the introduction of cellular communications into the UK is detailed together with some of the major parameters of the British system, and the progress that the network operators have made since the opening of the service at the beginning of 1985.

3.2 OPERATION OF A CELLULAR SYSTEM

The main parts of a cellular mobile radio network are the Mobile Switching Centre (MSC), the base stations and the mobile units. Communication to and from any mobile user is made via the base station serving the cell in which the user is situated. Each base station is equipped with a transceiver for each communication channel assigned to it, together with signal strength monitoring equipment and the necessary control equipment. Every base station is connected by dedicated links to the MSC through which all calls within the system are routed. The MSC controls and co-ordinates the activities of the base stations, interconnects the mobile system to the land telephone network and provides a centralised control point for the entire system. The mobile unit consists of a fully automatic frequency synthesised transceiver capable of tuning to any channel allocated to the system, together with a processor to conduct signalling and control functions necessary for the successful operation of the system.

To enable all the control functions of such a system to be performed, a few of the allocated radio channels are defined and used solely as 'control channels' rather than call ie. voice channels. These channels carry data used primarily for the exchange of information needed to establish and monitor calls. The number of these so called control channels is kept to a minimum by employing frequency re-use.

Whenever a mobile unit is turned on but not engaged in a call, the unit simply monitors a control channel. The unit itself selects which one of the various control channels to monitor by sampling the signal strength on all control channel frequencies. The mobile tunes to the channel with the strongest signal and synchronises with the data stream being transmitted on that channel by the system. The mobile unit remains on this channel until it either receives an incoming call, wishes to make an outgoing call, or until the signal level of the control channel requires that a new channel be selected.

When a mobile detects that it is being called, it quickly samples the signal strength on all control channels, thus enabling it to respond through the base station offering the strongest signal to the mobile at its current position. The mobile then transmits a 'ready' message back to the base station and waits for a reply. The system responds with a voice channel assignment signal, the mobile automatically tunes to the designated channel, and the call proceeds. Whilst the call is in progress, the base station examines the signal level that it is receiving from the mobile every few seconds. When this level becomes too low for the call to continue at a reasonable quality level the system looks for another base station which can offer a better quality signal. When a suitable base station is found the system sends a command to the mobile telling it to retune to a new channel associated with the new base station. Whilst the mobile changes to the new channel, the MSC re-routes the other party to the new base station. This process of transferring a mobile from one voice channel to another is termed 'hand-off' and causes a small break in the call when it occurs.

Although as far as the cellular user is concerned, operation is very simple and straightforward, the practical implementation is complex and involved. The existence of several different cellular systems in various countries means that it is not possible to give a detailed account of a cellular system which is correct for all schemes. However, this highly simplistic description, it is believed, does apply for all present operational systems.

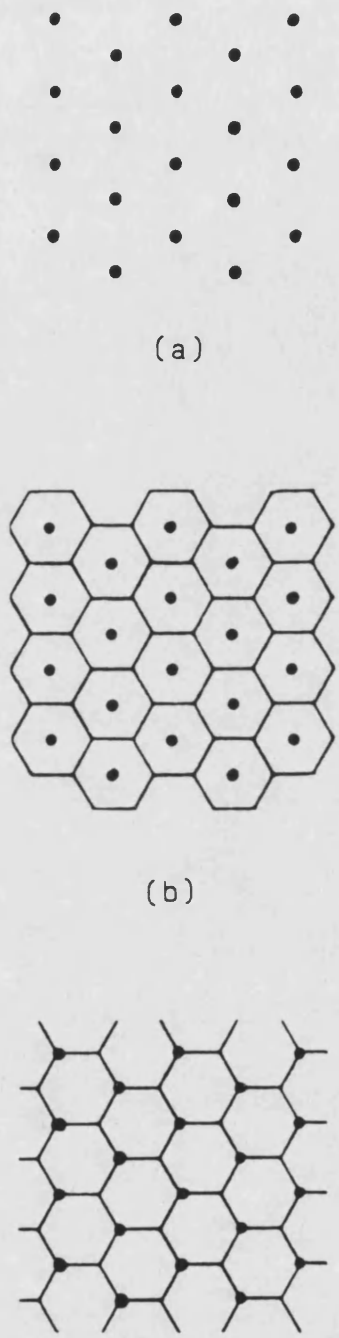
3.3 PRACTICAL REALISATION OF A CELLULAR SYSTEM

The implementation of the cellular concept in a practical mobile radio system necessitates the construction of an essentially regular array of base stations over the required coverage area, as illustrated in Figure 3.1a. In practice, the procurement of space and planning permission to enable this optimum distribution to be achieved is possibly one of the most difficult problems to overcome in engineering and installing a cellular system. More often than not this regular pattern must be approximated as closely as conditions permit. However, assuming that this idealised array of base stations can be realised, a pattern of regular hexagonal cells can be overlaid in various ways. Of these numerous possible overlays, two are of particular interest for cellular systems. These are

(1) when cell centres fall on base station sites,

(2) when half of the vertices of a cell fall on base station sites.

These two different possibilities are shown in Figure 3.1b and 3.1c and result in what is known as 'centre excited' (omni-directional) cells and 'corner excited' (directional) cells respectively.



(c)

• — Cell Site Location

Figure 3.1. Cellular Geometry With and Without Cells.

(a) Cell Site Lattice (b) Centre Excited Cells

(c) Corner Excited Cells

The centre excited cell is the traditional system used in many mobile radio systems, where a base station with an omni-directional antenna is located at the centre of the desired coverage area. (This does not include systems where quasi-synchronous or synchronous coverage techniques are employed [(1),(2),(3)].) In contrast, the corner excited cell is served by three base stations using directive antennae with a beamwidth of 120^{o}. These antennae are orientated as shown in Figure 3.2 so that the extensions of their main lobe lie along the sides of the hexagonal cells.

In the early days of a system it is more cost effective to use centre excited sites due to their lower initial cost. However, as the system grows and the number of users increases the use of corner excited cells becomes more attractive. In comparison with an omni-directional transmitting antenna, a directional antenna can provide the same signal level in the region that it serves whilst causing substantially less interference within co-channel cells which lie outside the main lobe. Similarly, a directional receiving antenna attenuates interfering signals received from mobiles at bearings not spanned by the main lobe. This gives corner excited cells the advantage of being able to operate with a lower re-use distance while still

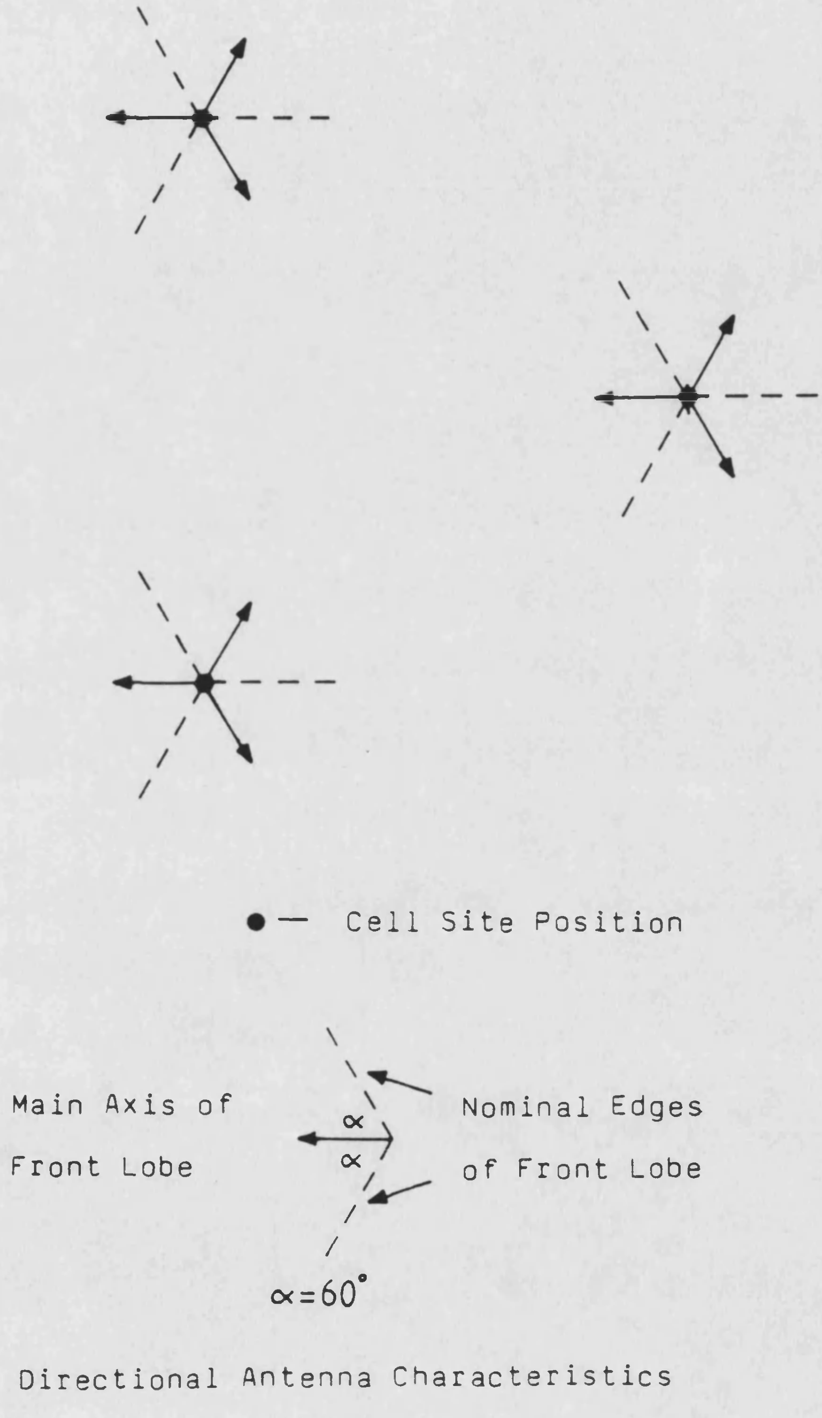


Figure 3.2. Orientation of Directional Antennae at Directional Cell Sites.

keeping co-channel interference to a sufficiently low level. Since a reduced re-use distance is synonymous with a smaller number of cells per cluster, or more to the point, a smaller number of channel sets, each corner excited site has the capability of supporting more users. This thereby reduces the total number of sites needed for a given total load on the system. Hence, in a mature system, rural and low user density areas will continue to be served by centre excited cells whilst cities and higher user density areas are more likely to use the higher capacity corner excited cells.

3.4 SELECTION OF KEY PARAMETERS FOR A PRACTICAL SYSTEM

Before installing a cellular system, it is necessary to define some of the key parameters of the scheme. In the setting of these key parameters, the important objectives that generally must be met are cost restraints, good transmission quality and a large ultimate customer capacity. In some contexts, conflicts appear among these objectives and trade-offs must be made so that no one objective is seriously undercut to benefit another.

3.4.1 Cell Radius

Defining the maximum cell radius to be used in a system at its inception is part of the general problem of achieving a satisfactory compromise between the two objectives of low cost and good transmission quality. The maximum cell radius has only an indirect effect on the ultimate capacity of the system. This is in complete contrast to the minimum cell radius, the cell radius after the final stage of cell splitting, which has little effect on the system cost per customer or transmission quality, but plays a vital part in setting the ultimate system capacity.

The cell splitting procedure cuts the cell radius by a factor of two and the cell area by a factor of four. Thus it is the ratio between the maximum and minimum cell radius which determines the number of cell splits that can take place in a system. As previously mentioned, cell splitting can, in principle, be repeated an indefinite number of times. However, from the point of view of practical considerations, decreasing the cell size beyond certain bounds leads to problems with the location of base station sites and burdens the MSC with performing frequent hand-offs. In such a situation a significant proportion of the MSC processor's capacity is consumed by performing hand-offs with obvious reductions in carrying out other important duties.

The sound quality of all calls on a cellular system is intended to be comparable to that over the public switched telephone network. This sound quality can be directly related to the RF signal-to-noise (S/N) ratio present at the receiver input, which in turn is related to the power output of the transmitters and the characteristics of the antennae being used. Assuming that transmitter powers and antennae characteristics have been established, it is the value chosen for the maximum cell radius that effectively determines the minimum RF S/N ratio that a system will experience. This minimum ratio, however, must still be sufficient to provide the required sound quality.

Hence the maximum cell radius is dependent on subjective and statistical factors. To meet this sound quality objective, subjective tests can be performed to enable a value of S/N ratio to be determined above which this criterion is met. The statistical propagation characteristics encountered in LMR systems can then be used to set an upper limit on the cell radius such that there is a high probability that this level will be exceeded throughout the system.

The cell radius is obviously a parameter for which many factors must be taken into consideration before a value is chosen.

3.4.2 Co-channel Re-use Ratio

The previous discussion in section 3.3 has explained the economic incentive for minimising the ratio of D, the distance between co-channel cell sites, to R, the cell radius. This co-channel re-use ratio (D/R) also has an impact on both the transmission quality and the ultimate capacity of the system. The influence on transmission quality arises because the D/R ratio affects the co-channel interference levels. Since this ratio determines the number of channels per channel set, it also sets a limit on the traffic carrying capacity of each site, which in turn governs the ultimate customer capacity of the system.

Making D/R as small as possible serves the objectives of low cost and large capacity. On the other hand, making the ratio as large as possible benefits transmission quality. As in the determination of the cell radius, a compromise among objectives is necessary. In order to obtain the required level of sound quality within the system, there must be a sufficient level of signal as oppose to co-channel interference present at the receiver input. It is this required signal-to-interference (S/I) ratio which must be met throughout the system which determines the necessary trade-off between the objectives. This is again dependent on the same subjective and statistical factors as discussed in the previous section on the cell radius.

In mature systems, two or more sizes of cells will simultaneously exist in a coverage area. Special care must be taken to ensure that the correct minimum distance, D exists between cell sites equipped with the same voice channels. This is however, not the only requirement since D/R must be maintained in an area where multiple cell sizes mean that the radius, R of a cell has different values for different sites. This problem can be overcome by operating the large and small cells on different channels of the same channel set. This does, however, reduce the customer capacity of the cells and when these capacities are reached can force the larger cell to undergo cell splitting to enable the full channel set to be allocated to each cell to restore maximum traffic capacity back to the cells.

3.5 CELLULAR MOBILE RADIO IN THE UK

In 1979 the World Administrative Radio Conference (WARC) allocated a section of frequency spectrum in the range 860-960MHz for mobile radio applications. On 25th June 1982 the British Government allocated 50MHz of this 900MHz band to be used for a cellular mobile radiotelephone system, together with the terms and conditions for two national cellular radio networks. The Government decided to licence two companies to operate the two cellular networks. These two operators were Racal-Millicom (Operating) Limited, now known as Racal-Vodafone (Holdings) Limited, a private joint venture company set up between Racal and Millicom Inc. of USA, and Telecom Securicor Cellular Radio (TSCR) Limited, a company set up between the then publically owned British Telecom and the private company Securicor Limited. The 25 year licences were granted in May 1983 and February 1984 respectively and stipulated that the operators should commence service by 31st March 1985 and cover an area representing 90% of the UK population (corresponding to approximately 65% of the total UK land area) by 1990.

The objective of licencing two and only two companies was to ensure effective competition between the two network operators, and also between the manufacturers of the system equipment. However, the Government wished that the two networks be compatible such that a subscriber to either network could change to the other if desired without changing his or her mobile equipment. The approach adopted was to define the overall system to be used by the two operating companies to ensure adequate interworking, but to restrict the depth of this definition to enable the two operators to compete in terms of technology, pricing and quality of service. The two companies were also not allowed to participate in the design, manufacture or sale of the mobile equipment. This has since been altered with the revision of the licences permitting the two operators to sell to government departments and crown agencies.

The need to introduce the service quickly precluded any attempt to design a completely new system, and it was clear that an existing cellular system would have to be chosen, at least as a basis of the design, and developed accordingly. After discussions between the Government and the two operators, it was announced in February 1983 that the already proven AMPS system would be the design base for the UK system. In July 1983 the specification of the UK system, which would be known as the Total Access Communications System (TACS), was published. Although largely similar to the AMPS system, some major modifications had been made to meet UK and European requirements. The main changes were in the radio parameters and performance specification. Although still operating in a duplex FM mode, the channel spacing was reduced to the European standard of 25kHz, together with a corresponding lowering of the peak frequency deviation of the system. A further consequence of the reduction in channel spacing was a decrease in the data rate of the system from 10kbit/s to 8kbit/s. The frequency bands stated in AMPS lie partly within the European Band V television broadcast band and so had to be changed for TACS. The two bands allocated were slightly wider than AMPS and located at 890-915MHz for mobile transmission and 935-960MHz for base station transmission. This gave a total of 1000 duplex channels available to the two networks, although at present only 600 channels have been allocated to the two networks, 300 to each operator, the remaining 400 being held back for the introduction of the Pan-European system. Table 3.1 contains a comparison between the AMPS and TACS systems parameters. (A more detailed account of the TACS system can be obtained by reading some of the many papers that have been published on the subject [(4),(5),(6)].)

Parameter	TACS	AMPS
Frequency Band (MHz)		
(i) mobile Tx	890-915	825-845
(ii) base station Tx	935-960	870-890
Maximum Number of Channels	1000	666
Channel Spacing (kHz)	25 (with 12.5kHz offset)	30
Transmit to Receive Spacing (MHz)	45	45
Peak Frequency Deviation (kHz)		
(i) speech	9.5	12
(ii) signalling	6.4	8
Signalling Data Rate (kbit/s)	8	10

Table 3.1. A Comparison of TACS and AMPS Radio Parameters.

By January 1985 both operators had commenced public operation and were offering service in the London area. Since then, the coverage area of both networks has been expanding rapidly. At the end of 1985 both operators had extensive coverage over London, the Home Counties, the Midlands, Manchester and Liverpool and the principal motorways. The TSCR network, known as 'Cellnet' boasted 27,000 users, almost 10,000 more than expected, whilst 20,000 people were subscribing to the Vodafone system [7]. By the end of 1986 it is expected that both companies will offer coverage of all major cities and routes within the UK.

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CHAPTER FOUR

INTERFERENCE IN LAND MOBILE RADIO SYSTEMS

4.1 INTRODUCTION

The explosive growth of mobile radio systems combined with the low level of new spectrum allocations to such schemes has led to the LMR service becoming increasingly troubled by high levels of interference. Possibly one of the most common and most difficult to solve sources of interference in radio systems is that caused by intermodulation. Unfortunately the requirement for several systems to cover the same area together with the use of narrow channelised frequency bands has resulted in the employment in LMR systems of configurations that are extremely prone to the generation, and hence problems associated with this type of interference.

A second and just as problematical source of interference is that caused by frequency re-use. In the early days of mobile radio it was possible to allocate new channels to each new system installed. Unfortunately, the growth within the service meant that this situation soon came to an end and, despite numerous reductions in channel spacings, it became necessary to re-use channels in different parts of the country so introducing for the first time the possibility of co-channel interference. However, the siting of co-channel transmitters was such that sufficient geographical separation existed between them to ensure that throughout the service area of each base station, signals from distant co-channel transmitters were always below the front end noise level of receivers.

The ever increasing demand for mobile radio systems has unfortunately now reached the point where co-channel transmitters can no longer have separations as before. Channels are now being re-used at distances that can produce significant levels of co-channel interference, and hence the service areas of base stations have become limited by co-channel interference rather than by front end noise.

This chapter discusses the mechanism behind the generation of intermodulation products, and highlights those products which are generally regarded as troublesome to LMR systems. Attention is also given to the possible sources of intermodulation interference in land mobile schemes. The problems of co-channel interference are also discussed and it is shown that due to the propagation characteristics of the mobile radio channel, the prediction of absolute levels of co-channel interference is not possible. Such interference levels have to be presented in statistical form and this is done for both a single co-channel interferer and for six co-channel interferers.

4.2 INTERMODULATION INTERFERENCE

4.2.1 Generation Mechanism

Intermodulation (IM) is a multiple signal interference mechanism where two or more signals mix in a non-linear device to produce products at frequencies other than those of the input signals. The frequencies at which these IM products can occur may be easily derived from the mathematical analysis of such a device, but the absolute amplitude and phase of the products are more difficult to calculate. Their dependence on many factors, including the strength of the signals, the extent of the non-linearity, and the frequency relationship between the signals make it impossible to determine these quantities without the use of analytical models whose parameters are determined by measurements of the specific non-linearity [1].

A non-linear device can be represented by means of the polynomial transfer characteristic

$$g(v) = A_0 + A_1 v + A_2 v^2 + A_3 v^3 + \ldots\ldots + A_n v^n \quad (4.1)$$

where v defines the excitation, g(v) is the output or response of the device, and A_0, A_1, A_2, etc. are constant coefficients.

For a truly linear system all coefficients of the characteristic except A_1 are zero, and in practical systems which aim to be linear it is usual to find $A_0 = 0$ and $A_1 >> A_2 >> A_3$ etc. such that the polynomial can be truncated, although this need not always be the case.

If the non-linearity is subjected to r unmodulated sinusoidal carriers of frequencies f_1, f_2, ... f_r, then an IM product will be generated whose frequency, f_x is described by

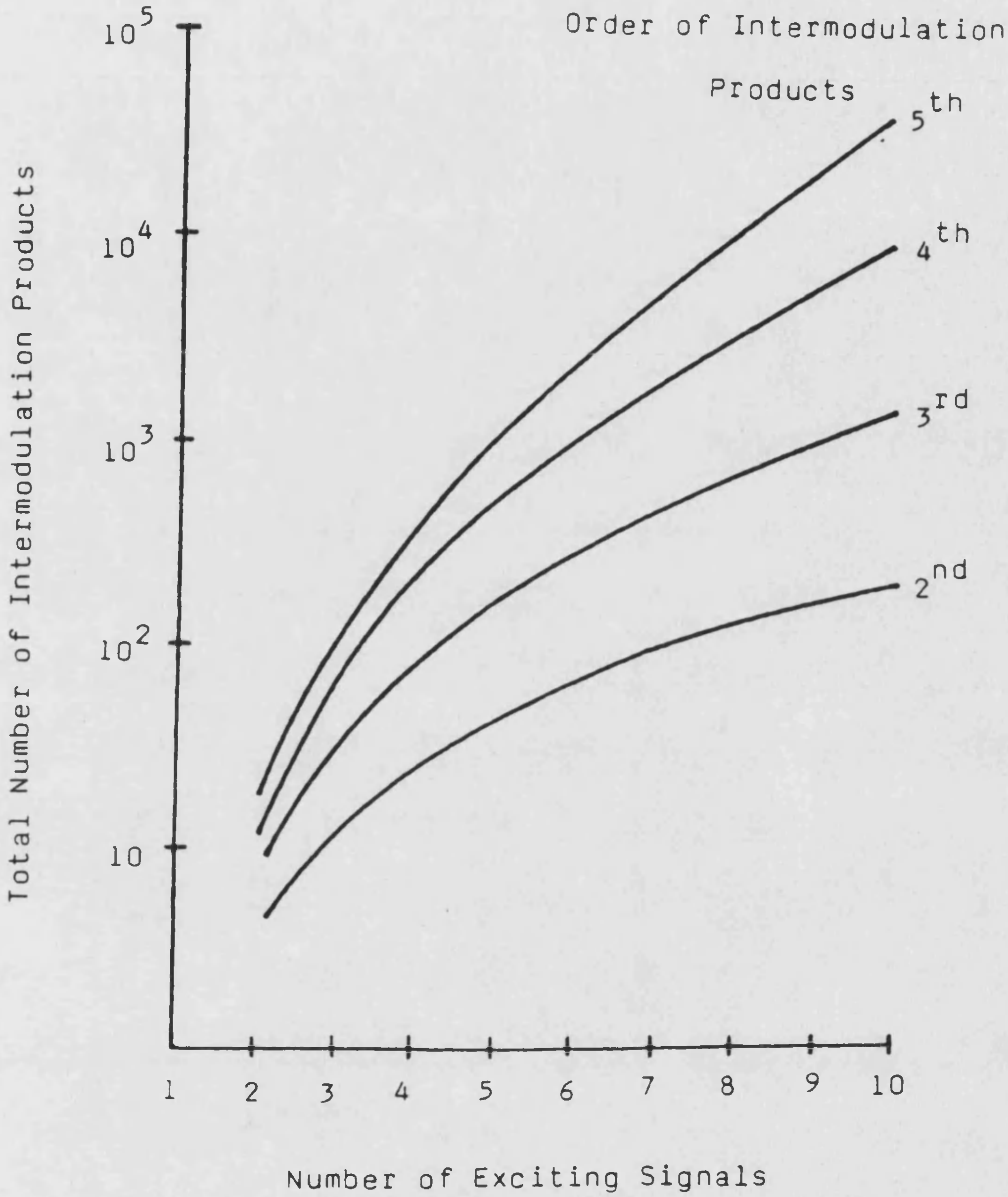
$$f_x = mf_1 + nf_2 + \ldots\ldots + yf_r \tag{4.2}$$

where m, n, ..., y are positive or negative integers and $|m| + |n| + \ldots\ldots + |y|$ signifies the order of the IM product.

For example, if we consider excitation by two sinusoids of frequencies f_1 and f_2, then 3^{rd} order IM products will be generated at frequencies equal to $(2f_1 + f_2)$, $(2f_1 - f_2)$, $(2f_2 + f_1)$, and $(2f_2 - f_1)$. If we introduce a third sinusoid of frequency f_3, then 3^{rd} order products will also be generated at $(f_1 + f_2 - f_3)$, $(f_2 + f_3 - f_1)$, $(f_1 + f_3 - f_2)$, and $(f_1 + f_2 + f_3)$. From this example it can be seen that all the 3^{rd} order products have been derived by taking all possible combinations of the exciting frequencies three at a time. This can be extended to say that all 4^{th} order products are generated by taking all possible combinations of the input signals four at a time, 5^{th} order by taking five at a time, etc. Generalisation of this leads to the statement that all n^{th} order products are formed by taking all possible combinations of the exciting signals n at a time.

As the number of exciting carrier signals increases, the number of IM products that can be generated by the non-linear device rises rapidly. Figure 4.1 shows the relationship between the number of exciting signals and the number of IM products generated up to 5^{th} order [(2)].

Modulated signals can be considered as a cluster of exciting sinusoids covering the range $f_c \pm \Delta$ where f_c is the nominal frequency of the carrier and Δ is the half bandwidth of the modulated signal. Each component can be regarded as one of the inputs to the device so broadening the IM spectral line. The extent of the broadening is dependent on the bandwidth occupied by the contributing modulated signals and the multiplication factor of that contribution. For modulated signals occupying the same bandwidth, the maximum spread of a product is $\pm n\Delta$ where n is the order of the product.



Note. The total number of IM products includes positive and negative frequencies. The number of positive ie. real frequencies, is always greater than 50% of the total shown, the actual percentage being dependent on the numerical values of the fundamental frequencies.

Figure 4.1. Effect of the Number of Exciting Signals on the Generation of Intermodulation Products.

The spectral range that can be occupied by IM products is thus vast. Even order products can extend from dc at the lower end to n times the highest frequency at the upper end. Odd order products have a slightly reduced range from the smallest difference between two signals to n times the highest frequency. Although there is no theoretical limit to the number of IM products that can be obtained, only a relative few are of consequence in mobile radio systems.

IM products, although always being a potential source of interference, become particularly troublesome when they fall on a frequency assigned to a receiver which is situated close to the source of the IM. In the worst case, this interference can be so severe as to over-ride the wanted signal, obliterating it completely. More commonly though, the strength of the product may be insufficient to cause total disruption of communications, but rather to degrade the quality to a varying extent. Other situations may arise when it merely results in causing annoying break-through and bursts of noise and garble when the channel is not in use.

In LMR systems, the use of frequencies in relatively small channelised bands means that only the odd order products of the form $(2f_1 - f_2)$, $(3f_2 - 2f_3)$, and

$(f_1 + f_2 - f_3)$ can possibly fall within the band of operation of a scheme and hence cause interference problems. It is also helpful that in almost all cases of IM, as the order of the product increases its amplitude decreases. Thus the higher the order of the product the smaller the amplitude and hence the lower the level of interference. It is usually only the 3^{rd} and 5^{th} order products which have sufficient amplitude to be troublesome, although under certain conditions the magnitude of products up to 11^{th} order have been known to cause problems.

The fact that most of the IM products generated within a system are not detrimental to that particular scheme does not mean that they can be ignored and forgotten about. It is highly probable that some of these will fall within frequency bands of other radio systems causing interference. Thus it is important to follow good engineering practice and design and install systems so as to minimise the generation of all IM products, not only for the sake of the system concerned but also for all other radio spectrum users.

4.2.2 Sources of IM Generation

The mechanism for generating IM products with the potential of causing interference exists in 3 major categories in mobile radio systems.

(1) In all radio transmitters that are situated in close proximity to other transmitters.

(2) In all receivers that are subject to a multiplicity of strong signals.

(3) In antenna feed systems, towers, rusty or corroded metal structures, electrical wiring, etc. (commonly known as the 'rusty bolt' effect.)

The need for more than one mobile radio system to cover the same geographical area has led to the sharing of facilities for transmission and reception at favourably located rooftop or hilltop sites. This has created sites where many transmitters and receivers are closely located to one another, and consequently is a likely place for IM to occur. The primary source of IM generation in this area is the mutual interaction of transmitter output circuits through antenna-to-antenna coupling [3]. The power output from one transmitter can be radiated into the antennae of other transmitters. This results in signals from each transmitter entering the final amplifier stages of other transmitters. Any non-linearity in these amplifiers makes them act as mixers, mixing their own signal and those entering via the antenna. The products produced are then re-radiated by the antenna and can be received as interference.

Maintaining isolation between the outputs of a number of transmitters sharing a site is a formidable task. Location of the antennae on the mast such that good isolation exists between them is usually impossible without sacrificing area coverage. The solution to the problem has been to couple a number of transmitters operating in the same frequency band together so that they can be connected to a single aerial. This allows a known degree of isolation to be inserted between the transmitters, and also reduces the number of antennae required at a base station site. Unfortunately, to perform this multi-coupling of transmitters requires the use of components which can introduce their own spurious outputs. The use of isolation and combining components containing non-linear materials ie. ferrite, and wideband amplifiers operating supposedly in a truly linear mode can all give rise to the generation of IM products.

The coupling of many receivers to a single antenna is also common practice nowadays. Such a system usually employs a wideband linear distribution amplifier. Coupling between transmitter and receiver antennae or a mobile close in to the site can cause this arrangement to become a generator of IM interference. The huge dynamic range that exists between transmitter output powers and receiver sensitivities means that this distribution amplifier can be driven into a non-linear mode hence creating IM products. Even frequencies which are slightly outside the passband of the amplifier can still be strong enough to cause problems.

The final cause of IM interference at a site is probably the least common, but undoubtably the most difficult to find and prevent. The existence of corroded joints or contacts on or around a site present further areas with non-linear characteristics. Illumination of these junctions by transmitter antennae leads to the generation and re-radiation of unwanted spurious outputs with the potential to cause IM interference.

So far the generation of IM products has concentrated on the base station site where, it is agreed, most IM interference originates. However, the mobile receiver is another prime place for such spurious outputs to be formed. The front end of the receiver is to a degree a non-linear device and so has the potential to generate IM products. A product generated by receiving two or more strong signals either from a base station or from other mobiles in the vicinity can fall on a channel frequency assigned to the mobile for reception and hence cause interference problems.

4.3 CO-CHANNEL INTERFERENCE

Co-channel interference is experienced in radio systems whenever the received level of a wanted signal, s_1 does not exceed the received level of a unwanted signal being transmitted on the same frequency, s_2 by a satisfactory amount. This can be expressed more succinctly by the expression for the occurrence of co-channel interference of

$$s_1 \leq r s_2 \tag{4.3}$$

where r is the protection ratio, the minimum ratio of wanted to unwanted signal level for satisfactory reception for the type of modulation being used [4].

In LMR schemes both base stations and mobiles can suffer from co-channel interference. The siting of base stations on prominent pinnacles and the fact that mobiles spend most of their time in highly built-up urban/suburban areas, together with the difference in base station and mobile transmitter output powers generally found in LMR schemes means that the mobile is more likely to receive signals from co-channel base stations than a base station is to receive signals from co-channel mobiles. Thus it is the mobile that usually suffers with problems of co-channel interference, although in conditions of anomalous propagation both mobile and base station can be subject to severe levels of such interference.

The level of co-channel interference that will be experienced in a system will understandably depend upon several factors. One of the major factors is obviously the propagation characteristics that are encountered in LMR schemes. The subject of radiowave propagation in the mobile environment is one that has received considerable attention over the years resulting in the publishing of several classic papers [(5),(6),(7),(8)]. In a typical mobile radio situation, the propagation between base station and mobile is rarely by a direct line-of-sight route, but via a multitude of different routes. The lack of a unique propagation path between transmitter and receiver causes the instantaneous level of the received signal to exhibit a highly variable structure with the motion of the mobile.

It is generally agreed [(9)] that propagation in LMR systems can be divided into three distinct factors.

(1) An inverse fourth power dependence of mean received signal power on the distance between transmitter and receiver.

(2) A shadowing effect caused by the diffraction of radiowaves around buildings and other terrain features.

(3) A fast fading effect due to a standing wave pattern set up by the multiple reflections of radiowaves from objects in close proximity to the mobile.

All of these have been considered in great detail previously [10], and the statistical nature of the shadowing and fading effects are well known. If we assume for the moment that the received signal power is solely dependent on an inverse fourth law relationship with distance, then the level of a wanted signal, m_1 received by a mobile from a base station will be given by

$$m_1 = \frac{K}{d_1^2} \tag{4.4}$$

and similarly, the level of the unwanted signal, m_2 from the co-channel transmitter is given by

$$m_2 = \frac{K}{d_2^2} \tag{4.5}$$

where the transmitters are assumed to be identical, K is a propagation constant common to both, and d_1

and d_2 are the distances from the mobile to the wanted and unwanted base stations respectively.

Combining equations 4.4 and 4.5 gives

$$\frac{m_1}{m_2} = \frac{d_2^2}{d_1^2} \tag{4.6}$$

Thus if fading and shadowing effects are ignored, the expression for the occurrence of co-channel interference can be written as

$$\frac{s_1}{s_2} = \frac{m_1}{m_2} = \frac{d_2^2}{d_1^2} \leq r \tag{4.7}$$

This defines a sharp boundary between co-channel and no co-channel interference areas as the locus of $d_2/d_1 = \sqrt{r}$. However, in a practical mobile system the fluctuations in received signal level mean that it is not possible to ignore fading and shadowing effects without producing an unreasonably optimistic view. Unfortunately, the statistical nature of these phenomena mean that in practice there is no simple boundary that exists between areas with and without co-channel interference and hence such interference can only be measured in terms of probabilities.

Using the relationships that have been derived for the fluctuating mobile signal [11], it is possible to calculate the probability of co-channel interference occuring under fading and shadowing conditions in terms of the protection ratio, r, and the standard deviation of the shadowing, σ, being experienced by the mobile. Figure 4.2 [11] shows the probability of co-channel interference with shadowing and fading effects taken into consideration. R is the protection ratio expressed in dB, the three values of σ are for different areas of location of the mobile ie. usually between 6 and 12dB in urban areas and below 6dB in rural areas, and m_{d1} and m_{d2} are the area means of the wanted and unwanted signals respectively. It can be seen that high levels of co-channel interference can occur even near the wanted transmitter where the mean level of the wanted signal is much greater than that of the unwanted signal.

So far only one co-channel transmitter has been considered when predicting co-channel interference levels. In most systems, especially cellular type systems, there is more than one unwanted signal. In this situation the probability of co-channel interference occuring becomes expressible by

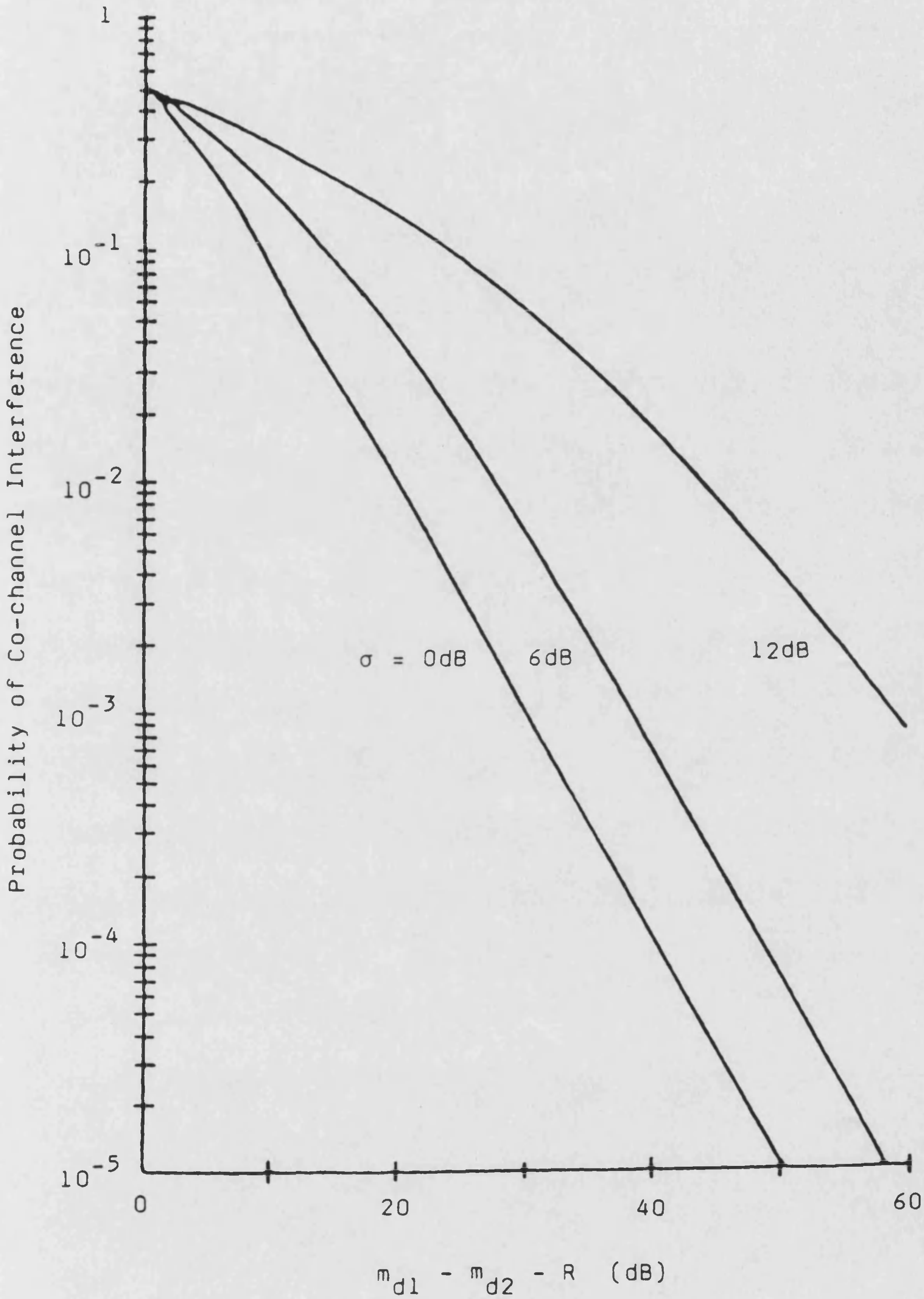


Figure 4.2. Probability of Co-channel Interference with Fading and Shadowing for a Single Co-channel Transmitter.

$$s_1 \leq r \sum_{j=1}^{n} s_j \qquad (4.8)$$

where n is the number of co-channel signals.

For six co-channel transmitters located as shown in Figure 4.3 the probability of co-channel interference is as shown in Figure 4.4 [12]. A comparison of Figures 4.2 and 4.4 show that there is a significant increase in the probability of co-channel interference for six interfering signals over that for just a single interferer.

In the calculation of these co-channel interference probabilities it has been assumed that the fading and shadowing in the wanted and co-channel signals are uncorrelated. This is certainly true for the fading, but the shadowing may be partially correlated and so the assumption has the effect of making the predictions pessimistic. It is also assumed that the standard deviation of the wanted signal, σ_1 and that of the interfering signal(s), σ_2 are equal, which is a reasonable assumption since shadowing is primarily a function of the topography near to the mobile.

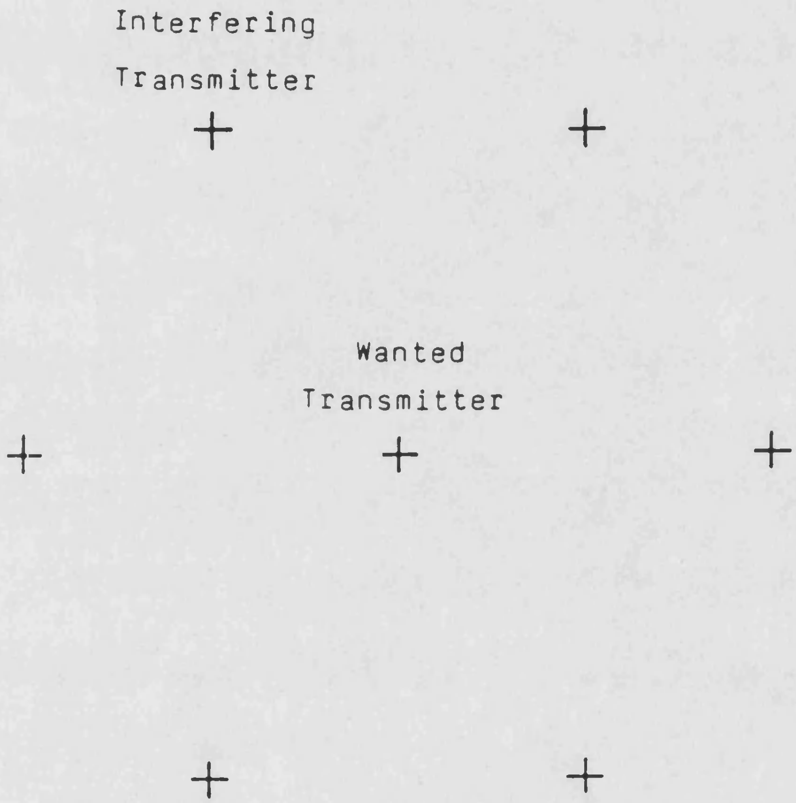


Figure 4.3. Geographical Location of Six Co-channel Transmitters.

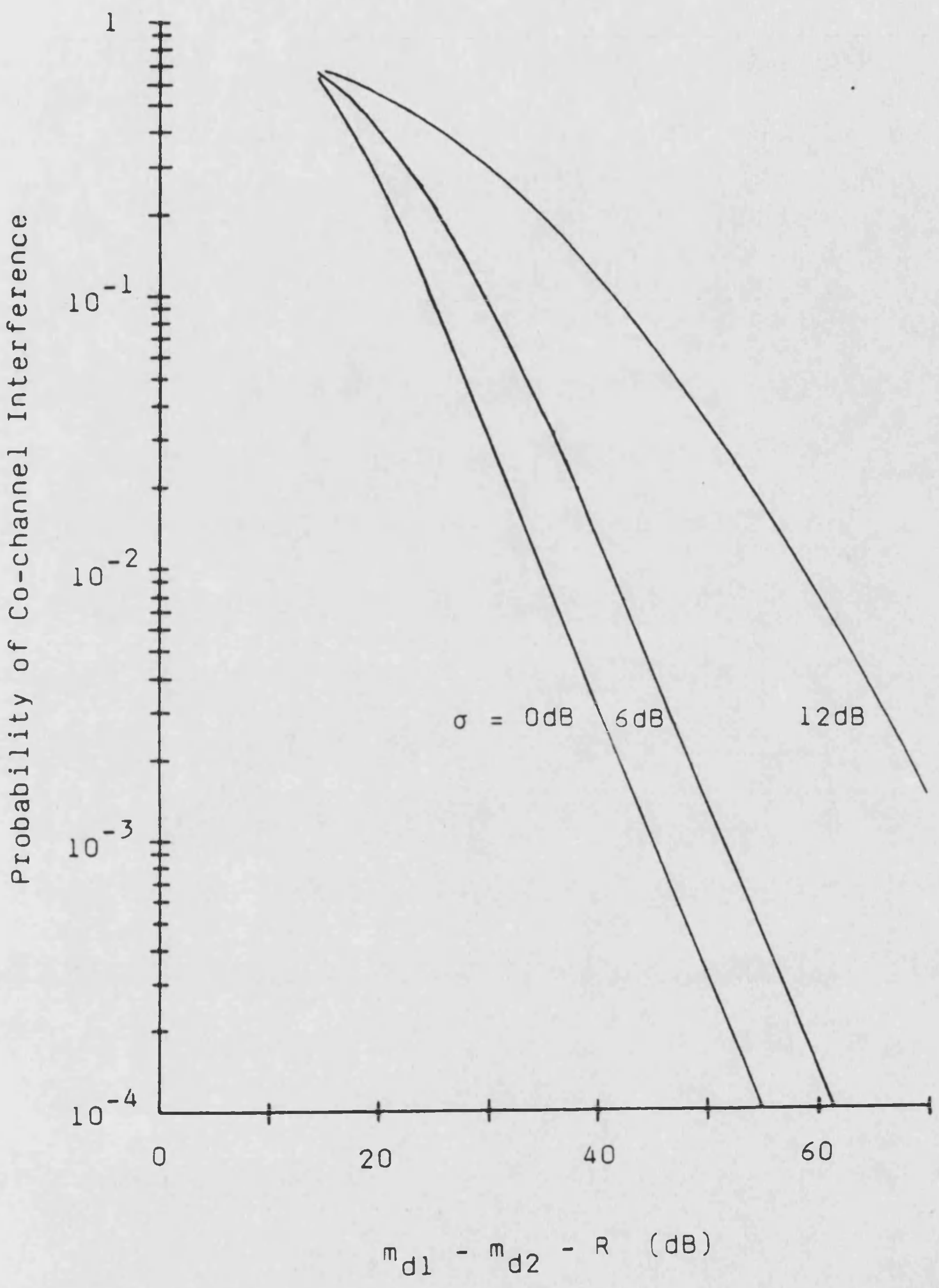


Figure 4.4. Probability of Co-channel Interference with Fading and Shadowing for Six Co-channel Transmitters.

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CHAPTER FIVE

POWER CONTROL OF RADIO TRANSMITTERS IN LAND MOBILE RADIO SYSTEMS

5.1 INTRODUCTION

Despite all the time and effort afforded to eliminating the problems of interference in the expanding LMR service, the existence of IM and co-channel interference seems, unfortunately, to have become a fact of life. The inability to completely remove such troublesome effects makes the necessity to keep this type of interference to a minimum an obvious one. Hence, any technique that could bring about a reduction in the levels of either should be pursued, with special attention being given to schemes which could help achieve a reduction in both.

The frequency re-use feature of cellular schemes makes for efficient spectrum utilisation, but as these systems become established the inevitable problem of co-channel interference associated with such a technique will become all too apparent. In previous conventional systems, co-channel interference has generally existed between schemes operated by different organisations, and so, since the level of such interference has been under the control of other co-channel systems, has remained relatively unchecked. However, in the case of cellular type schemes, co-channel interference can and will exist between service areas of the same system. Transmitting more power than is absolutely necessary in one cell can lead to higher levels of interference being experienced in other co-channel cells, and as a result, cellular schemes could well find themselves in the ridiculous situation of being 'self co-channel interference' limited.

One obvious solution to this co-channel interference problem is to control the output power of transmitters such that the radiated power is kept to the minimum necessary level to provide adequate communication quality. Many current cellular systems already employ such a scheme to varying extents in order to enable the output power of mobile transmitters to be regulated in this manner under control from the base station. This not only reduces the possibility of their signal being picked up by distant co-channel base stations, but prevents desensitisation at the local base station receiver and hence the consequential generation of IM interference. The extension of such power control to base station transmitters has the potential to bring about a significant reduction in the high levels of co-channel interference present in cellular mobile reception, thus making such schemes more operable and hence effectively more efficient than they otherwise would be.

This chapter investigates the subject of transmitter power control together with its applications in LMR and other types of radio communication systems. Concentration is however, centred on the LMR aspects of power control, particularly those of cellular, and the advantages to be gained from its use. Consideration is given to the reduction of generated IM interference at cellular base station sites due to the introduction of output power control in mobiles, and details the extent of such control presently used by current systems. The reduction of co-channel interference by the use of base station power control is also discussed, and some indication is given as to the decrease in interference that could be expected from the implementation of such a scheme.

5.2 BACKGROUND AND AREAS OF APPLICATION OF TRANSMITTER POWER CONTROL

Transmitting more power than is absolutely necessary in a radio system is not only wasteful but potentially harmful to other radio spectrum users, either directly through operation on the same channel or adjacent channels or indirectly by overloading circuits to cause IM. For a large part of the time the power radiated from a transmitter is far in excess of that necessary to provide the required communication quality. However, the use of a system that enabled transmitter output powers to be controlled in accordance with the variations in the transmission characteristics of the radio channel would enable the correct level of power to be maintained at all times. The usefulness of such a concept has been shown by the describing of several situations in which the use of transmitter power control could be advantageous.

It is believed that the first systems to make use of transmitter power control were the tropospheric scatter schemes used in long range microwave links. This type of radio system has always been prone to problems associated with enhanced propagation caused by ducting conditions. Although enhanced propagation conditions affect most radio communication systems to some extent in one way or another, the range of enhancement encountered in tropospheric scatter systems is such that the received signal level can rise by as much as 50dB or more above the mean value. This large increase causes the receiver to become saturated, usually in the low noise front end amplifier, and results in the output becoming distorted. This obviously causes problems with the availability and reliability of this type of communication system. However, more serious from the point of view of other radio users is the interference effects which tropospheric scatter signals, subject to enhancement, can have on other systems, especially on line-of-sight microwave links.

Although the problem of excessive receiver level could be overcome by increasing the dynamic range of the receiver, assuming that this was indeed possible, it is evident that the only way to overcome the interference problem is to transmit the signal at a level which more or less matches the propagation conditions. In 1976 a configuration aimed at achieving this control of transmitter power was reported [1]. The scheme, which was then being developed by Marconi Communications Systems was a fully automatic system and allowed the output power level of the transmitter at one end of the link to be controlled by the signal strength of the incoming signal at the receive end. 1978 saw the installation of the system for the first time in part of a network of tropospheric scatter circuits for communications with North Sea oil platforms (2).

Two other situations in which a variable level of transmitter power could be of significant benefit have been described (3). The first is connected with the extended battery life that could be achieved in mobile equipment. The use of a mobile or hand portable unit for long periods of time without having access to new batteries or recharging facilities is quite possible in certain circumstances eg. mountain rescue services. The use of a fully automatic power control scheme under such conditions could significantly extend the time for which the mobile equipment could be used, and hence increase the operating efficiency and ability of the radio unit.

The second set of circumstances under which a transmitter power control scheme could be advantageous is concerned with the operation of radio equipment on a spectrally quiet basis ie. communication security. The use of power control for such a purpose can be appreciated by the fact that it is more difficult to intercept a radio signal if that signal is being transmitted with low power. A power control system operating such that transmitters powers are kept to the minimum level necessary for satisfactory communication to be achieved could be a simple and effective way to ensure that interception by a third party is made more difficult.

Another area in which transmitter power control has been considered is in its application to spread spectrum LMR systems. The growth in the number of multi-access mobile radio systems presently being installed and considered has fueled research into the use of spread spectrum techniques for such schemes. There have been several papers published extolling the virtues of these techniques, especially for small area cell coverage systems [(4),(5),(6)] where it has been shown [(7)] that FM systems can become limited from adjacent and co-channel interference. One of the advantages illustrated by all the authors is that as the cell size in such systems is reduced, the number of simultaneous users within the cell per MHz of occupied bandwidth that a spread spectrum scheme can support can significantly exceed that of FM systems. However, it has been pointed out [(8)] that such results have almost certainly been obtained by assuming that the signal level from each mobile unit is received at the base station at exactly the same level. To enable this situation to be realised in practical systems requires each mobile transmitter to have a power control system such that the output power of the equipment can be remotely controlled by the base station thus affecting the necessary power equalisation.

The implementation of transmitter power control in cellular systems can be seen to help solve two major problems associated with this type of scheme. Firstly, the use of power control for mobile transmitters can help alleviate the IM problems encountered in the use of base station receiver distribution amplifiers, the need for which is brought about by the requirement to connect several receivers to a single antenna. Secondly, the use of transmitter power control at base station sites can mean a reduction in the levels of co-channel interference experienced by mobiles in cellular systems, especially in areas where small cell sizes are present. Both of these applications will now be considered in more detail.

5.3 POWER CONTROL OF MOBILE TRANSMITTERS IN CELLULAR SYSTEMS

In cellular systems, as in most other multi-channel radio schemes, the inability to have a separate receiving aerial at base station sites for each channel necessitates the use of coupling procedures to enable many receivers to be connected to a single antenna. Such multi-coupling schemes generally employ a wideband linear distribution amplifier after the necessary filtering as shown in Figure 5.1, but unfortunately this can lead to the generation of IM products and the consequential problems of IM interference.

The signal received at a base station from a mobile has a dynamic range which is dependent on the size of the coverage area of the base station. Even for relatively small service areas this dynamic range can be quite large and hence, the aerial distribution amplifier must be linear not only over the required frequency range, but also over the wide range of possible received signal levels. These are very demanding requirements, and are unfortunately not usually realisable in practice, thus guaranteeing the existence of a certain degree of non-linearity in the device.

If it is assumed for the moment that this non-

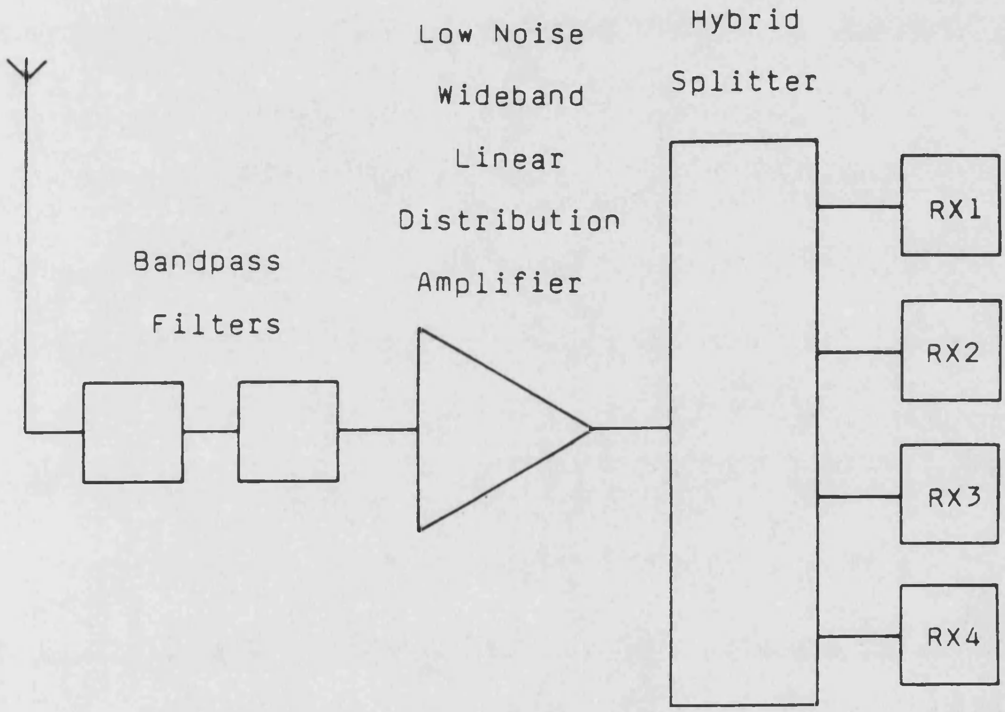

Figure 5.1. Base Station Receiver Multi-coupling.

linearity can be limited to the third order, then the transfer characteristic of the amplifier can be written as

$$g(v) = A_0 + A_1 v + A_2 v^2 + A_3 v^3 \qquad (5.1)$$

where $g(v)$ is the output or response of the device, A_0, A_1, A_2, and A_3 are constant coefficients, and v is the signal present at the input to the device.

Assuming that there are three mobiles communicating through the base station, then considering unmodulated carriers, v can be written in the form

$$v = a\cos\omega_1 t + b\cos\omega_2 t + c\cos\omega_3 t \qquad (5.2)$$

where a, b, and c are the signal magnitudes and ω_1, ω_2, and ω_3 are the channel frequencies on which the mobiles are operating.

The corresponding output of the amplifier is then given by

$$g(v)=A_0+A_1(a\cos\omega_1 t+b\cos\omega_2 t+c\cos\omega_3 t)+A_2(a\cos\omega_1 t+b\cos\omega_2 t$$
$$+c\cos\omega_3 t)^2+A_3(a\cos\omega_1 t+b\cos\omega_2 t+c\cos\omega_3 t)^3 \qquad (5.3)$$

Now

$$(a\cos\omega_1 t+b\cos\omega_2 t+c\cos\omega_3 t)^2=\frac{a^2}{2}(1+\cos 2\omega_1 t)+\frac{b^2}{2}(1+\cos 2\omega_2 t)$$

$$+\frac{c^2}{2}(1+\cos 2\omega_3 t)+ac\cos(\omega_1+\omega_3)t$$

$$+ac\cos(\omega_3-\omega_1)t+ab\cos(\omega_1+\omega_2)t$$

$$+ab\cos(\omega_2-\omega_1)t+bc\cos(\omega_2+\omega_3)t$$

$$+bc\cos(\omega_3-\omega_2)t \qquad (5.4)$$

and

$$(a\cos\omega_1 t+b\cos\omega_2 t+c\cos\omega_3 t)^3=(\frac{3a^3}{4}+\frac{3ab^2}{2}+\frac{3ac^2}{2})\cos\omega_1 t+(\frac{3b^3}{4}$$

$$+\frac{3a^2b}{2}+\frac{3bc^2}{2})\cos\omega_2 t+(\frac{3c^3}{4}+\frac{3b^2c}{2}$$

$$+\frac{3a^2c}{2})\cos\omega_3 t+\frac{a^3}{4}\cos 3\omega_1 t+\frac{b^3}{4}$$

$$\cos 3\omega_2 t+\frac{c^3}{4}\cos 3\omega_3 t+\frac{3ab^2}{4}$$

$$\cos(2\omega_2+\omega_1)t+\frac{3ab^2}{4}\cos(2\omega_2-\omega_1)t$$

$$+\frac{3ac^2}{4}\cos(2\omega_3+\omega_1)t+\frac{3ac^2}{4}$$

$$\cos(2\omega_3-\omega_1)t+\frac{3a^2b}{4}\cos(2\omega_1+\omega_2)t$$

$$+\frac{3a^2b}{4}\cos(2\omega_1-\omega_2)t+\frac{3a^2c}{4}$$

$$\cos(2\omega_1+\omega_3)t+\frac{3a^2c}{4}\cos(2\omega_1-\omega_3)t$$

$$+\frac{3bc^2}{4}\cos(2\omega_3+\omega_2)t+\frac{3bc^2}{4}$$

$$\cos(2\omega_3-\omega_2)t+\frac{3b^2c}{4}\cos(2\omega_2+\omega_3)t$$

$$+\frac{3b^2c}{4}\cos(2\omega_2-\omega_3)t+\frac{3abc}{2}$$

$$\cos(\omega_1+\omega_2+\omega_3)t+\frac{3abc}{2}\cos(\omega_1+\omega_2-\omega_3)t$$

$$+\frac{3abc}{2}\cos(\omega_1+\omega_3-\omega_2)t+\frac{3abc}{2}$$

$$\cos(\omega_2+\omega_3-\omega_1)t \qquad (5.5)$$

Thus the spectrum of the output is as shown in Figure 5.2. The amplitudes of the products are shown diagrammatically as decreasing with order number as an aid to clarity rather than indicating their actual magnitude. This example is for the particular case when $\omega_1 - \omega_2 \neq \omega_2 - \omega_3$ ie. non equally spaced channels. If the channels were equally spaced then some of the IM products would actually fall on the channel frequencies under consideration, a point that will be considered in far greater detail in the following chapter.

Equations 5.4 and 5.5 show how the amplitudes of the products are dependent on the magnitudes of the incoming signals, A_0, A_1, A_2, and A_3 being fixed for a particular device. Second and third harmonic amplitudes

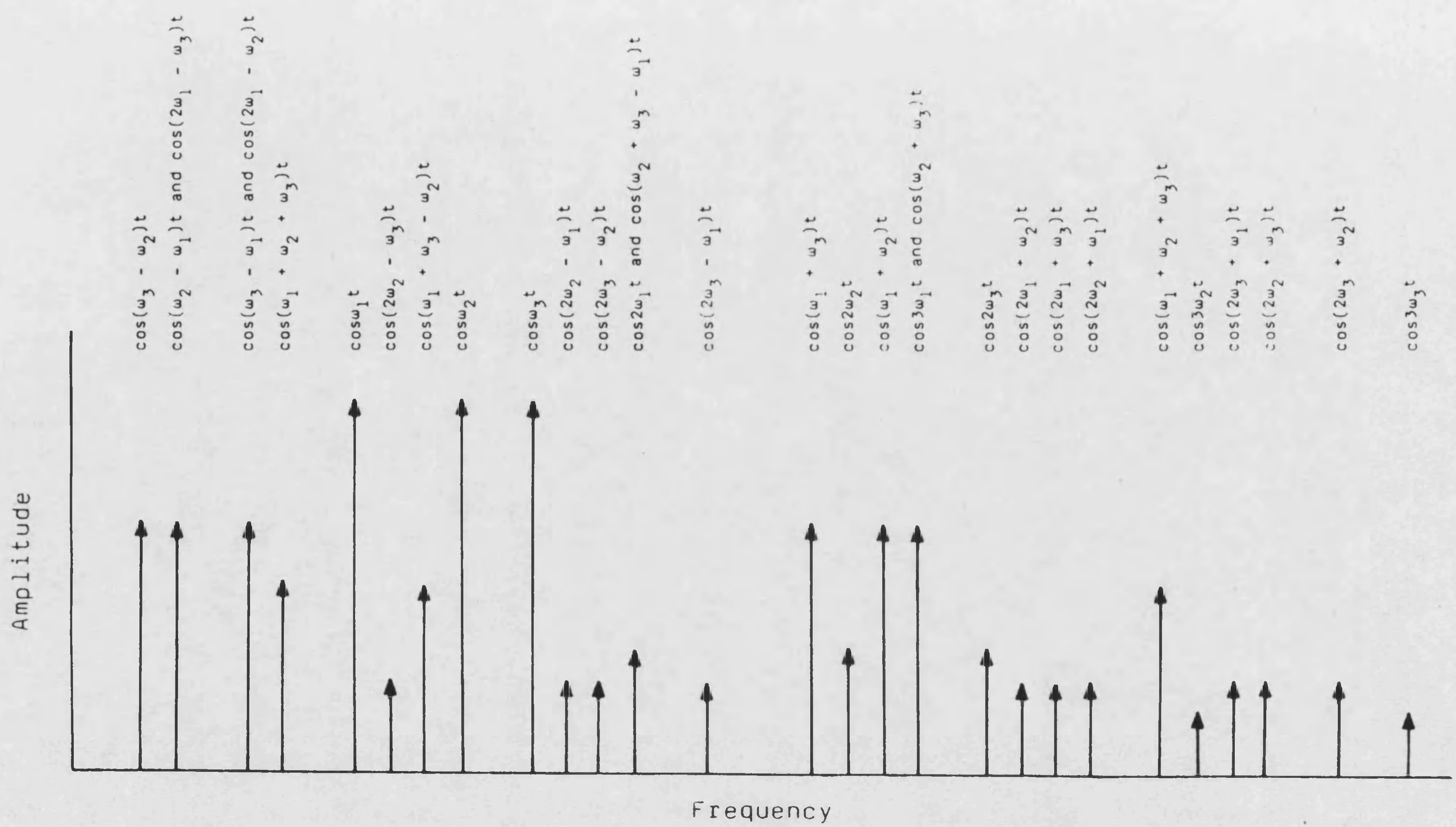

Figure 5.2. Spectral Distribution of Second and Third Order Intermodulation Products for a Third Order Non-linearity Excited by Three Unmodulated Carriers.

are proportional to the square and cube of the relative signal amplitudes respectively, however it is the magnitude of the more troublesome third order products that is of particular interest. The amplitude of 2-frequency products can be seen to be dependent on the magnitude of combinations of two of the incoming signals, whereas the 3-frequency products have amplitudes that are governed by the magnitude of all three of the signals. The multiplicative nature of third order product amplitudes means that as the levels of the incoming signals increase the magnitude of the products can increase at a much greater rate. For instance, for 2-frequency products, the existence of a squared term in the product amplitude means that a doubling in the received signal strength of this incoming signal can result in a fourfold increase in product magnitude. Doubling the amplitude of one of the other received signals would bring about a further twofold increase resulting in an overall eightfold increase in product level. For 3-frequency products a similar situation exists, in that a doubling of two of the received signals results in the product increasing by a factor of four, and a doubling in all three incoming signals means a factor of eight increase. Figures 5.3 and 5.4 illustrate this greater rate of increase in 2-frequency and 3-frequency third order product amplitudes

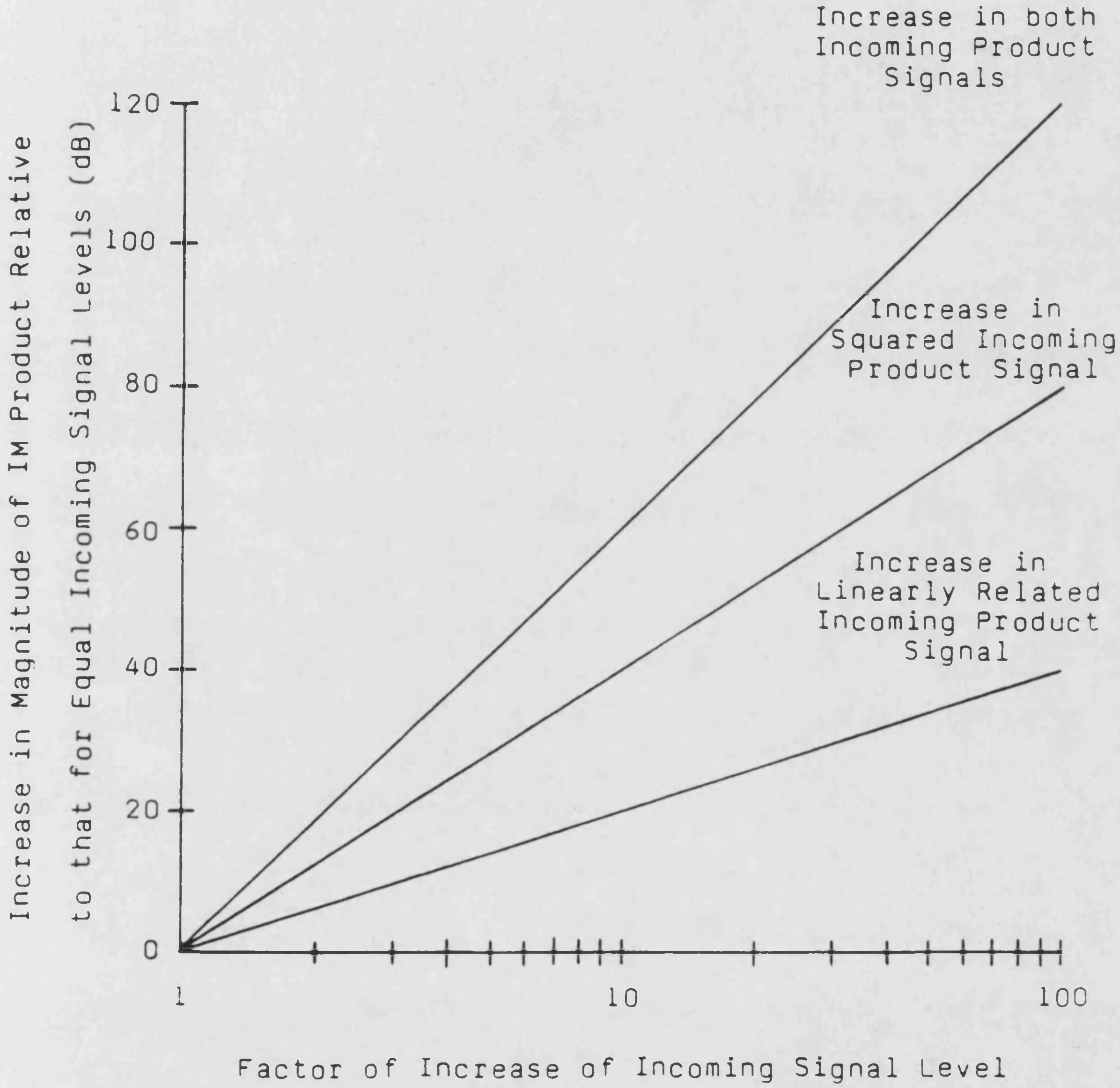

Figure 5.3. Increase in 2-frequency Third Order Product Amplitude with Increasing Incoming Signal Level.

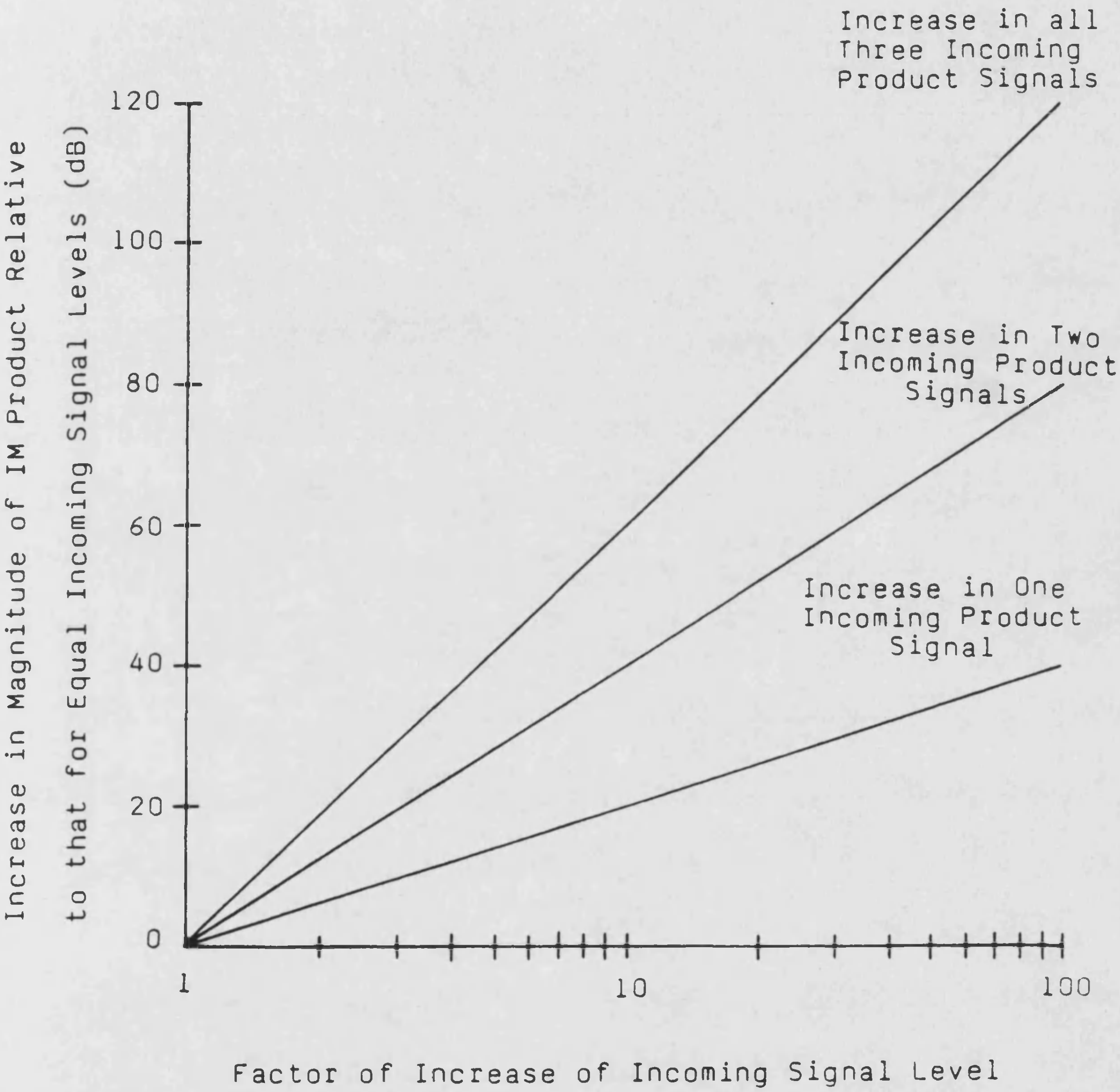

Figure 5.4. Increase in 3-frequency Third Order Product Amplitude with Increasing Incoming Signal Level.

respectively as the levels of the incoming signals are increased.

Mobiles communicating through the same base station are more likely than not to produce different magnitude signals at the common receiving antenna due to their differing locations and distance from the site. This variation in received levels can lead to IM products as mentioned above, being generated in the aerial distribution amplifier. Controlling the output power from mobile transmitters means that this dependence of received signal levels on distance can be removed thus enabling a more constant level to be received from a mobile irrespective of its position within the cell. This permits a more linear aerial amplifier to be built since the large dynamic range of mobile received signal powers no longer exists. Also if such a constant level is the minimum to provide satisfactory communication quality, then the amplitudes of any IM products generated in this manner are at their lowest possible level. This means not only lower in-band interference levels for cellular systems but also reduced levels of interference for other spectrum users. This constant low level of any generated IM products may be such so as to allow the use of frequencies in the area that were previously not possible due to the magnitude of IM interference levels. This could result in an effective increase in the spectral efficiency of not only cellular systems but other local radio schemes.

Present cellular systems have realised the benefits to be gained by using mobile transmitter power control and many current schemes now possess such a facility. The range of control over which the output power of mobiles may be changed varies from system to system, although all are consistent in using discrete power control steps. Table 5.1 gives the extent of power control together with the number of control steps for some of the current systems.

In the TACS system a further degree of power control exists in that there are four classes of mobile station each of which has a different nominal transmitter radiated power. These four classes and their corresponding output powers are given in Table 5.2. Mobile stations of class 1 may only be configured as vehicular mobile stations, and not as hand portables. Class 2 stations may be either vehicular mobiles or transportable stations, but again cannot be configured as hand portables. Only mobile stations of classes 3 and 4 can be used as hand portables. This restriction of hand portables to lower radiated powers helps counteract the problems of improved propagation associated

Cellular System	Mobile Power Control Range	Number of Power Levels
C-900	35dB	8
MATS-E	18dB	4
NAMTS	15dB	2
NORDIC 900	20dB	3
TACS	32dB	8

Table 5.1. Extent of Mobile Power Control in Some of the Current Cellular Systems.

Class of Mobile	Nominal Effective Radiated Power (ERP)
Class 1	10dBW (10.0 Watts)
Class 2	6dBW (4.0 Watts)
Class 3	2dBW (1.6 Watts)
Class 4	-2dBW (0.6 Watts)

Table 5.2. Nominal ERP for Each Class of Mobile Station in TACS.

with the operation of such units from within tall buildings. Table 5.3 gives the power levels and the corresponding radiated powers for the four different classes of mobile.

Mobile Station Power Level	Nominal ERP (dBW)			
	Mobile Station Power Class			
	1	2	3	4
0	10	6	2	-2
1	2	2	2	-2
2	-2	-2	-2	-2
3	-6	-6	-6	-6
4	-10	-10	-10	-10
5	-14	-14	-14	-14
6	-18	-18	-18	-18
7	-22	-22	-22	-22

Table 5.3. TACS Mobile Station Nominal Power Levels.

5.4 TRANSMITTER POWER CONTROL FOR CELLULAR BASE STATIONS

Common antenna working is now an established technique in multi-channel mobile radio systems. The multi-coupling procedures that are adopted at fixed station sites for the connection of several transmitters to a single antenna have already been mentioned in chapter four. Such techniques are valuable in that they not only avoid a proliferation of antennae, thus reducing the loading imposed on the mast, but also allow a known degree of isolation to be inserted between transmitter outputs so as to control the levels of IM generated at the site. There are several possible multi-coupling schemes that are available, the two extremes of which are shown in Figure 5.5. Unfortunately, the use of such configurations makes the implementation of power control at fixed sites questionable, and so up to now, has not been generally considered. However, the introduction of cellular type mobile radio systems has meant that base station power control may not only be a requirement, but a necessity if such schemes are to prove to be as effective as anticipated.

The high spectral efficiency associated with cellular type systems is essential if mobile radio is to

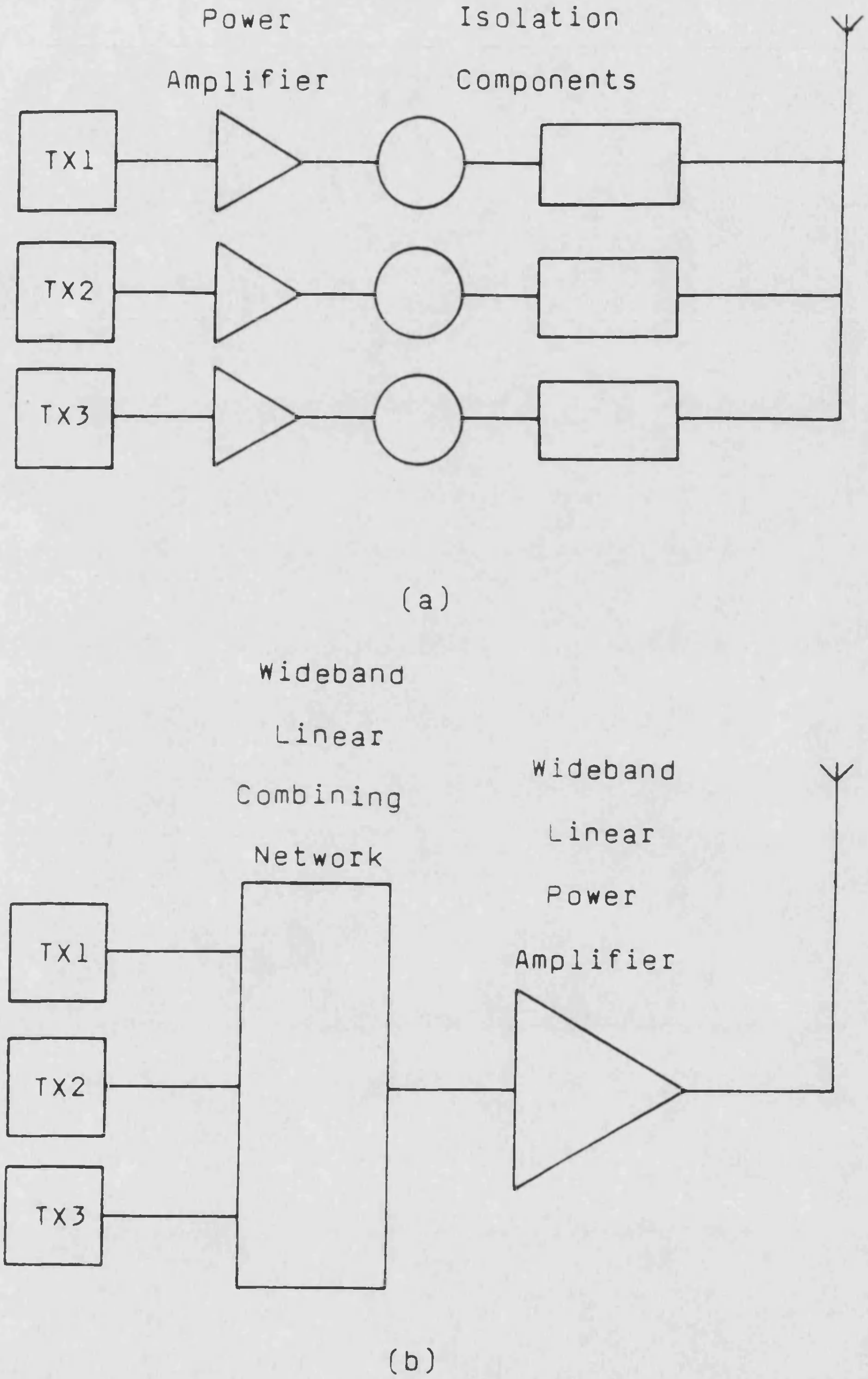

Figure 5.5. Multi-coupling of Base Station Transmitters.
(a) High Level Multi-coupling (b) Low Level Multi-coupling

continue to flourish. Unfortunately, to obtain this efficiency such systems possess a high degree of frequency re-use which immediately raises doubts about their co-channel performance. In an ideal situation it is possible for such systems to be organised so as to prevent co-channel interference being a problem. However, the existence of anomalous propagation conditions together with the unfavourable propagation characteristics encountered in the practical mobile communications environment threaten to produce high levels of co-channel interference for mobile reception which could severely limit the operational ability of these schemes, significantly reducing their efficiency. In order to alleviate the limitations imposed by mobiles receiving co-channel signals from surrounding base stations, cellular systems may well have to seriously consider the introduction of transmitter power control at base station sites.

If cellular systems were to implement base station transmitter power control, then in the same way as mobiles at present control output power to match the propagation conditions between cell site and mobile, base stations would do likewise. Thus, as a mobile moved around the coverage area of a base station the base station output power would vary between pre-defined maximum and minimum values depending on the transmission characteristics of the radio channel. If we assume for the moment that the propagation path between mobile and base station is solely dependent on distance, then base station power control can be seen to work such that when a mobile is at the cell boundary, the base station operates on maximum power and when a mobile is close in to the site, base station output power is at a minimum. Between these two points, the base station operates at some level in between these two limits. Assuming a simple inverse distance propagation law for mobile-base station transmission, an estimate of the reduction in average base station output power, together with the corresponding decrease in the level of co-channel interference can be obtained by considering a simple model of a cellular scheme. Considering the situation as shown in Figure 5.6 where two cells with circular service areas of radius R_o have base stations located at their centres which in turn are separated by a distance D_o. For a uniform distribution of mobiles within a cell, the probability of a mobile unit being within a circle of radius r, p(r), can be written as

$$p(r) = \frac{r^2}{R_o^2} \qquad (5.6)$$

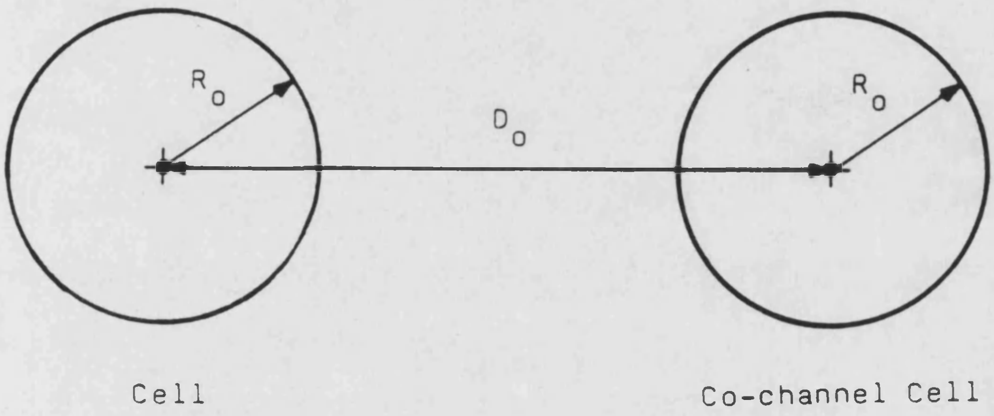

Figure 5.6. Simple Frequency Re-use Model of a Cellular Scheme.

If we assume a power control algorithm such that the variation in base station output power with mobile-base station separation, P(r), is given by

$$P(r) = P_o(\frac{r}{R_o})^{\alpha} \qquad (5.7)$$

where α is the propagation law index, and P_o is the power control range given by

$$P_o = P_{max} - P_{min} \qquad (5.8)$$

where P_{max} and P_{min} are the maximum and minimum base station output power levels respectively,

then the average base station transmitter power, P_{av}, can be estimated as

$$P_{av} = \int_{r=0}^{R_o} P_o(\frac{r}{R_o})^{\alpha} \frac{r^2}{R_o^2} dr + P_{min} \qquad (5.9)$$

which simplifies down to

$$P_{av} = \frac{P_o}{\alpha + 3} + P_{min} \qquad (5.10)$$

If the range over which the base station power can be controlled is sufficiently large such that P_o >> P_{min}, then equation 5.10 can be written as

$$P_{av} = \frac{P_o}{\alpha + 3} \qquad (5.11)$$

Thus, taking the commonly accepted value of $\alpha = 4$, the average reduction in the level of co-channel interference that could be expected in the other cell would be approximately 8.5dB. If we extend this model to consider the six nearest co-channel neighbours found in all practical cell cluster patterns, then assuming that interference from all six base stations is incoherent and independent so that addition of interference powers is applicable, the use of base station power control could result in a decrease in the average interference power for a cell of some 16.3dB. This figure is a little optimistic since it assumes that each base station transmitter is equi-distant from the co-channel mobile, a situation which is obviously only true if the mobile is located at the centre of its cell. However, if we consider the fact that there are not just the six nearest co-channel base stations, but several tiers of such transmitters located around a cell, then it could be argued that the reduction in interference from these sites through the use of base station power control could offset any error brought about by this assumption.

Referring back to Figure 4.4, it can be seen that such a reduction in co-channel interference power would bring about a significant decrease in the levels of this type of interference that are encountered in cellular schemes. In fact a comparison of Figures 4.2 and 4.4 show that as far as average co-channel interference levels are concerned, six co-channel base stations with power control could indeed be made to look like a single co-channel transmitter.

In the above discussion it has been assumed that we have continuous interference from co-channel base stations. In practice base stations only carry a limited amount of traffic and so continuous interference is at present a rare, if not somewhat pessimistic situation. However, with the rate at which subscribers to cellular systems are growing, such a situation can and will become a reality with which cellular systems must be able to cope.

The use of circular service areas for base stations has enabled a valid, although somewhat idealistic indication as to the benefit to be gained in co-channel interference performance of cellular systems from the implementation of base station power control. Unfortunately, this ideal coverage area of a base station transmitter, due largely to irregular terrain features, is far from achievable in practice. The inherent irregularities in service areas can lead to higher levels of co-channel interference than expected, and in some cases can make communication difficult if not impossible. It is under these conditions that base station power control could make a tremendous contribution to the operation and efficiency of cellular systems, giving mobiles, previously incapacitated through high co-channel interference levels, the possibility of being able to communicate once again.

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CHAPTER SIX

CHANNEL ASSIGNMENT STRATEGIES FOR CELLULAR SYSTEMS WITH POWER CONTROL

6.1 INTRODUCTION

In conventional LMR systems the effects of spectrum pollution by IM products can be extremely troublesome producing disruptive unwanted outputs on receivers whenever an IM product is present on-channel above the receiver sensitivity threshold. The problem is particularly severe in densely populated areas where very many base station transmitters share communal facilities and are assigned to channels which are closely packed in frequency. The multi-coupling procedures now adopted at many base station sites not only avoids an unnecessary proliferation of antennae, but by allowing a known degree of isolation to be inserted between transmitter outputs also serves to help control the levels of IM radiated from a site. In addition to this, great effort is afforded to the assignment of channel frequencies in a given area such that the generation of troublesome IM products by base station transmitters on other frequencies in use in the area is minimised.

In systems employing selective calling facilities, the problems of interference caused by IM products are reduced since the receiver mute will not 'lift' under conditions of interference inputs alone. Only when properly addressed will a receiver produce an audio output, and provided that the level of a wanted transmission is received with an appropriate protection ratio, then interference should not be significant. Cellular systems obviously fall into this category, and as such it is often argued that channel assignment strategies to minimise IM interference are irrelevant for this type of scheme.

At present, cellular systems take full advantage of this reduced vulnerability to IM interference by following simple channel assignment procedures which make no attempt to reduce the generation of on-channel IM products. However, the introduction of base station transmitter power control into cellular systems may necessitate the use of frequency assignment strategies which minimise troublesome IM products in order to avoid mobile receivers, under certain conditions, receiving on-channel products at a level in excess of that of a wanted signal. If a significant decrease in the efficiency of cellular systems due to a reduction in the number of channels that can be allocated to a cell is to be avoided, then the implementation of IM compatible assignments must be achieved with complete, or near complete utilisation of the available system channels.

This chapter discusses the channel assignment strategies presently adopted for conventional LMR systems in order to minimise IM interference problems. Consideration is given to the extent to which such strategies can go in avoiding on-channel products in practical systems, and the channel utilisation efficiencies that result. Factors governing the introduction of this type of channel plan into cellular systems are investigated and the maximum assignment efficiencies that can be expected from their implementation are presented for various different values of system parameters.

6.2 INTERMODULATION COMPATIBLE FREQUENCY ASSIGNMENTS FOR LMR SYSTEMS

Despite taking all necessary precautions to minimise the generation of IM products at source on base station sites, residual products still often exist, together with the possibility of IM generation in the mobile receiver. Although the frequencies at which IM products can occur are easily obtainable from the simple mathematical analysis of a non-linear device, the amplitudes of the products are somewhat more difficult to determine. Since it is not possible to predict product strengths or to tell whether or not a receiver is being driven beyond its linear operating characteristics, these problems of IM are usually avoided by judiciously selecting channel frequencies.

Frequency assignment strategies for conventional mobile radio systems rely on the division of the available spectrum into equi-spaced frequency intervals, and, ideally, utilisation of channels at any given site in such a way that no significant IM products from any combination of co-sited transmitter frequencies fall on any other channel in use in the vicinity. This capacity to assign IM compatible channels is feasible only if a large pool of frequencies is available from which compatible selections may be made. Obviously, in practical schemes such a resource of channel frequencies very rarely exists and so it is not possible to avoid all on-channel interfering IM products. If however, such a pool of frequencies did exist, then the implementation of an assignment that avoided all on-channel interfering products would result in large numbers of channels being classed as 'unusable' in areas around base stations, and consequently would provide an unacceptably low level of spectrum efficiency.

Although IM product amplitudes cannot be predicted, in general, the strength of the products in LMR systems decrease with increasing product order. As already mentioned in chapter four, this usually implies that it is sufficient to obtain only third and fifth order compatibility in channel assignments in order to avoid IM interference problems. In densely populated areas, the demand for channels is usually so great that this strategy is difficult to implement completely. However, in order to avoid unwanted mobile receiver outputs resulting from interference, implementation of at least third order compatible frequency plans is generally highly desirable. Unfortunately, the identification of such troublesome IM products in frequency assignments is usually a prolonged and monotonous task. Aids to simplify the process have, however been produced and the use of such procedures for generating IM interference free lists are now well established in the engineering of conventional mobile systems.

Over the years several different procedures have been established for producing channel assignment lists which are free from troublesome IM interference products [(1),(2),(3),(4),(5)]. These range from the early exhaustive testing techniques of Lustgarten [(1)] through to full computer analysis, and vary in the extent to which they identify interfering IM products. Some of these procedures produce assignments free of 2-frequency third order products of the form $(2f_1 - f_2)$, others include the 3-frequency third order products of $(f_1 + f_2 - f_3)$ form, whilst a few consider both third and fifth order products. The generality of certain processes enables them to be applied to the investigation of assignments free from even higher order products. However, such procedures usually employ computational techniques which in view of their time and cost aspects, together with the diminishing importance of higher order terms generally give such calculations negligible practical value. For the purposes of practicality, further concentration will be limited to the avoidance of third order IM products only.

Consideration of the IM generation mechanism in chapter four has shown that the frequency of a typical IM product, f_x can be given by

$$f_x = mf_1 + nf_2 + \ldots\ldots + yf_r \qquad (6.1)$$

where f_1, f_2, ... f_r are sinusoidal unmodulated carrier frequencies and m, n, ..., y are positive or negative integers such that

$$K = |m| + |n| + \ldots\ldots + |y| \qquad (6.2)$$

where K defines the order of the product.

It has been shown (6) that this IM product can only lie in the frequency band occupied by a desired signal if the following equation is satisfied.

$$m + n + \ldots\ldots + y = 1 \qquad (6.3)$$

For the case of third order products, the conditions for troublesome IM products are given by the two diophantine equations

$$|m| + |n| + |o| = 3 \qquad (6.4)$$

$$m + n + o = 1 \qquad (6.5)$$

Assuming that the frequency band under consideration is split into channels of equal width with no intervals between them, then extrapolation of these two equations leads to the simple fact that third order IM products are troublesome if any two of the differences between pairs of channels are identical. Thus to avoid on-channel third order products allocation of channels in a system must be staggered so that the spacing between any two channels in a block sequence is not repeated. Clearly then, in a multi-channel system with an IM compatible channel assignment, a mobile receiver must be capable of tuning over a frequency range in excess of that required from the simple consideration of the total number of channels in the system and the channel spacing. This so-called switching range, S can be defined by

$$S = C_n - C_1 + 1 \qquad \text{channels} \qquad (6.6)$$

where C_1 is the lowest channel, and C_n the highest channel that the mobile must be able to tune to in order to provide the requisite number of channels.

Evidently, from a mobile receiver-design point of view, the parameter S should be kept to a minimum value in order to achieve adequate front-end performance. The older style mobile transmitters employing separate channel crystals and multiplying circuitry also require S to be kept as low as possible since such problems as distortion and excessive dissipation can arise as such circuits are off-tuned. The use of final frequency voltage controlled oscillator (VCO) techniques has somewhat eased the problems of multi-channel transmitters, but the need to provide a high receiver selectivity still remains a trade-off with the bandwidth over which the equipment can be switched.

Figure 6.1 shows the minimum switching range required for systems with numbers of channels ranging up to 10 in order to avoid all third order IM. Two conditions are shown, the case when a system is permitted to operate with adjacent channels, and the situation when there must be at least one channel separation between operational channels. Figure 6.2 shows the minimum switching range for systems when only on-channel IM products of the form $(2f_1 - f_2)$ are to be avoided. The significant difference between the two graphs illustrates the more rapid growth of 3-frequency third order products over that of 2-frequency products as the number of channels within a system increases.

Since only a proportion of the channels within the switching range are used, the spectral efficiencies of third order compatible frequency plans, ie. the number

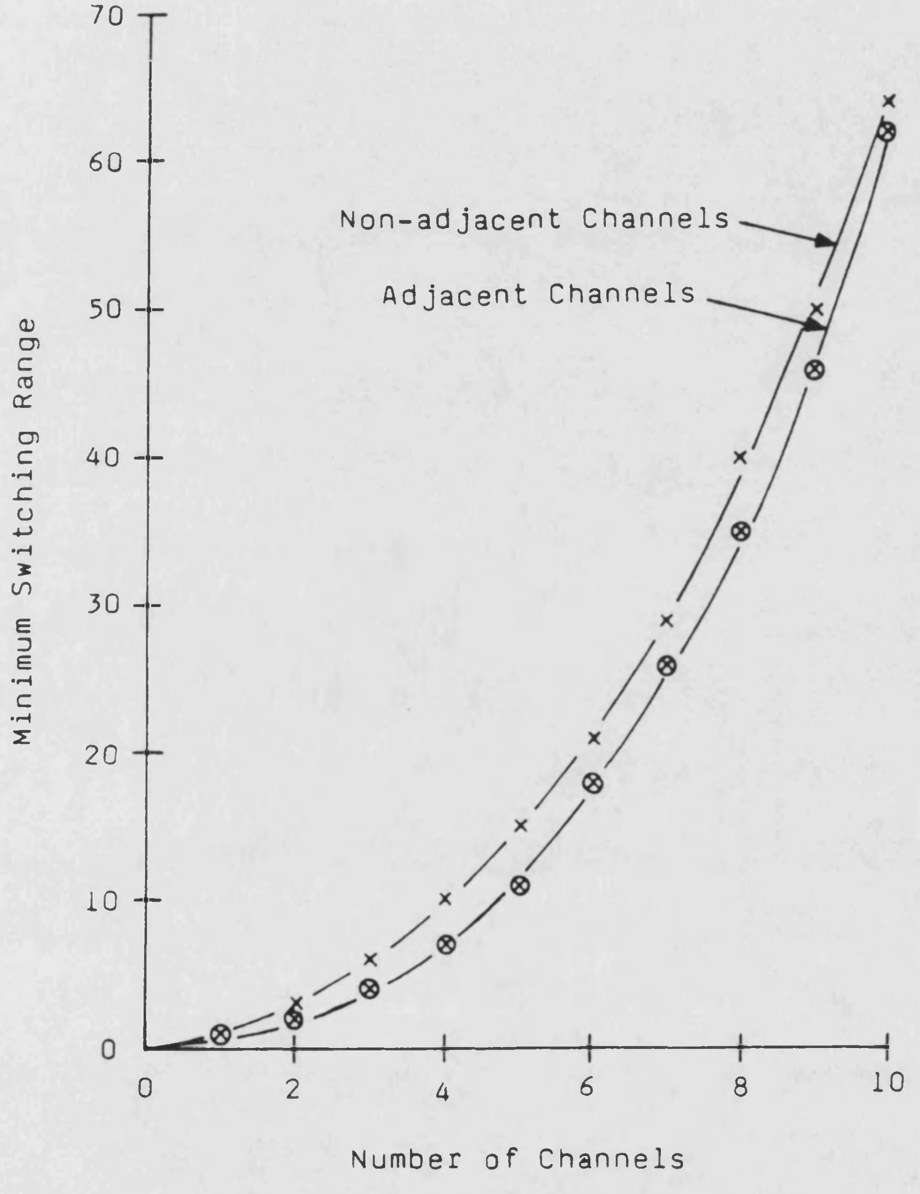

Figure 6.1. Minimum Switching Range Required to Avoid All Third Order Intermodulation Products.

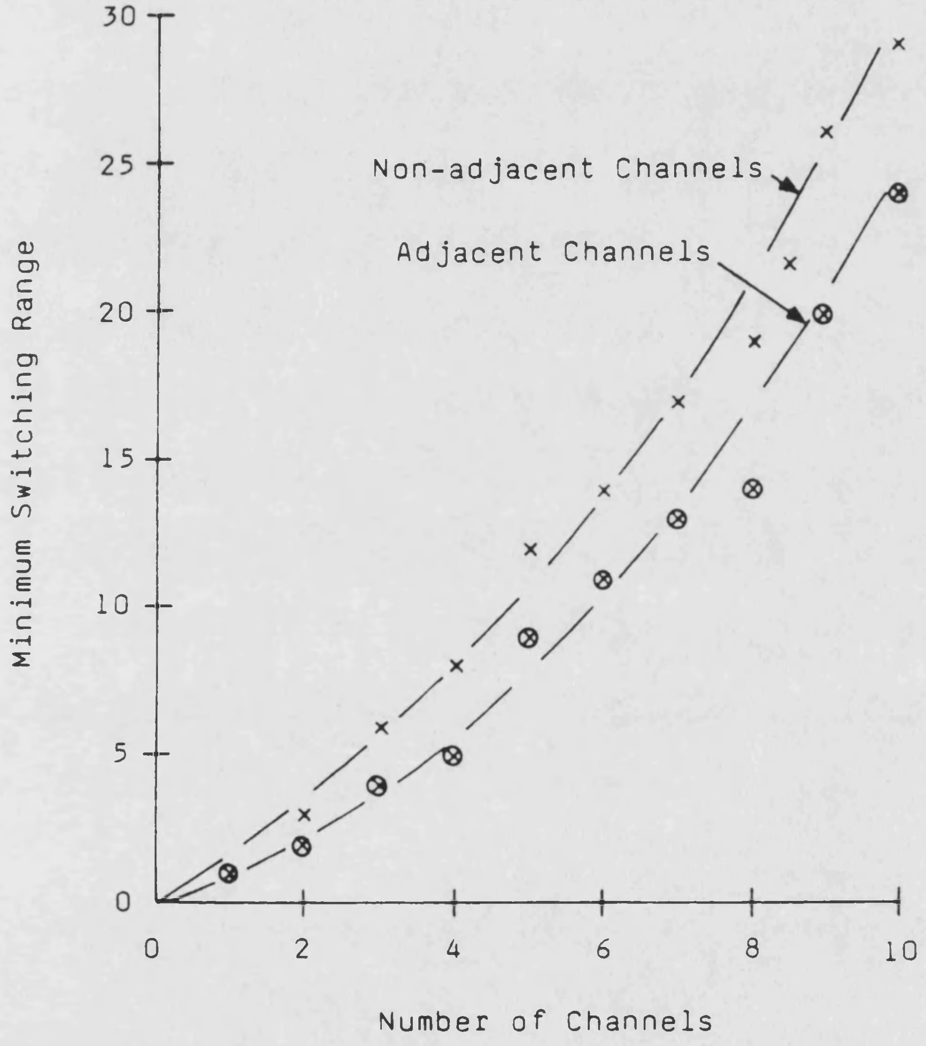

Figure 6.2. Minimum Switching Range Required to Avoid Only 2-frequency Third Order Intermodulation Products.

of channels that can be used from the total number of channels available, are naturally lower than those when no effort is made to avoid such IM problems. This is illustrated by Figures 6.3 and 6.4 which show the spectrum efficiencies of the two previous compatible channel assignments. Comparison between the spectral efficiencies of third order compatible and non-compatible frequency plans show a marked difference. However, such a direct comparison is unfair since although compatible assignments appear to be spectrally less efficient, the operational efficiency of a system with such channel plans is generally greater than one without due to its reduced association with IM interference, and hence the overall spectral efficiency is usually higher.

In the preceding discussion and preparation of third order compatible frequency plans it has been assumed that all channels consist of unmodulated carriers. This, clearly not being the case in practice, makes it necessary to consider the effects that transmission with modulation has on the generation of such channel assignments. It has already been mentioned in chapter four that for channels with modulations occupying the same bandwidth, an IM product can broaden by as much as $\pm n\Delta$, where n is the order of the product and Δ is the half bandwidth of the modulation. Thus for

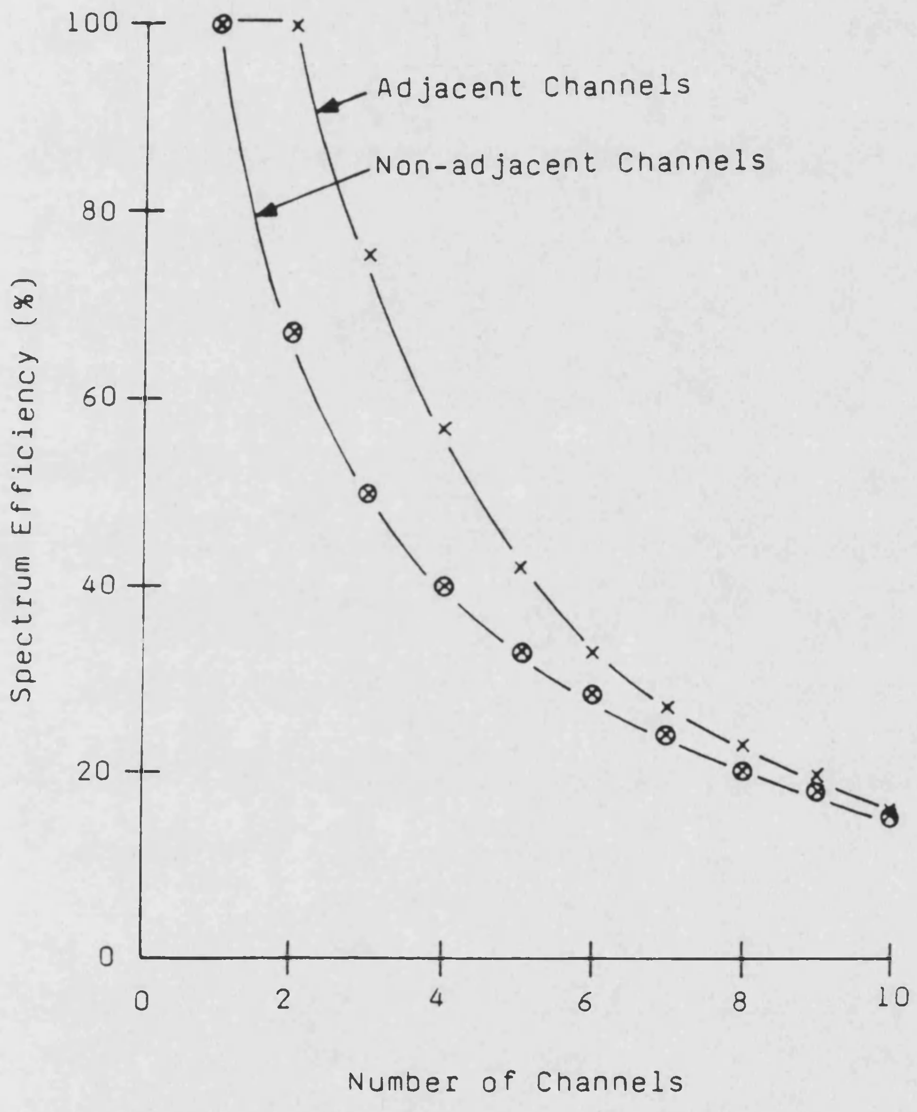

Figure 6.3. Spectrum Efficiency of Complete Third Order Compatible Frequency Assignments.

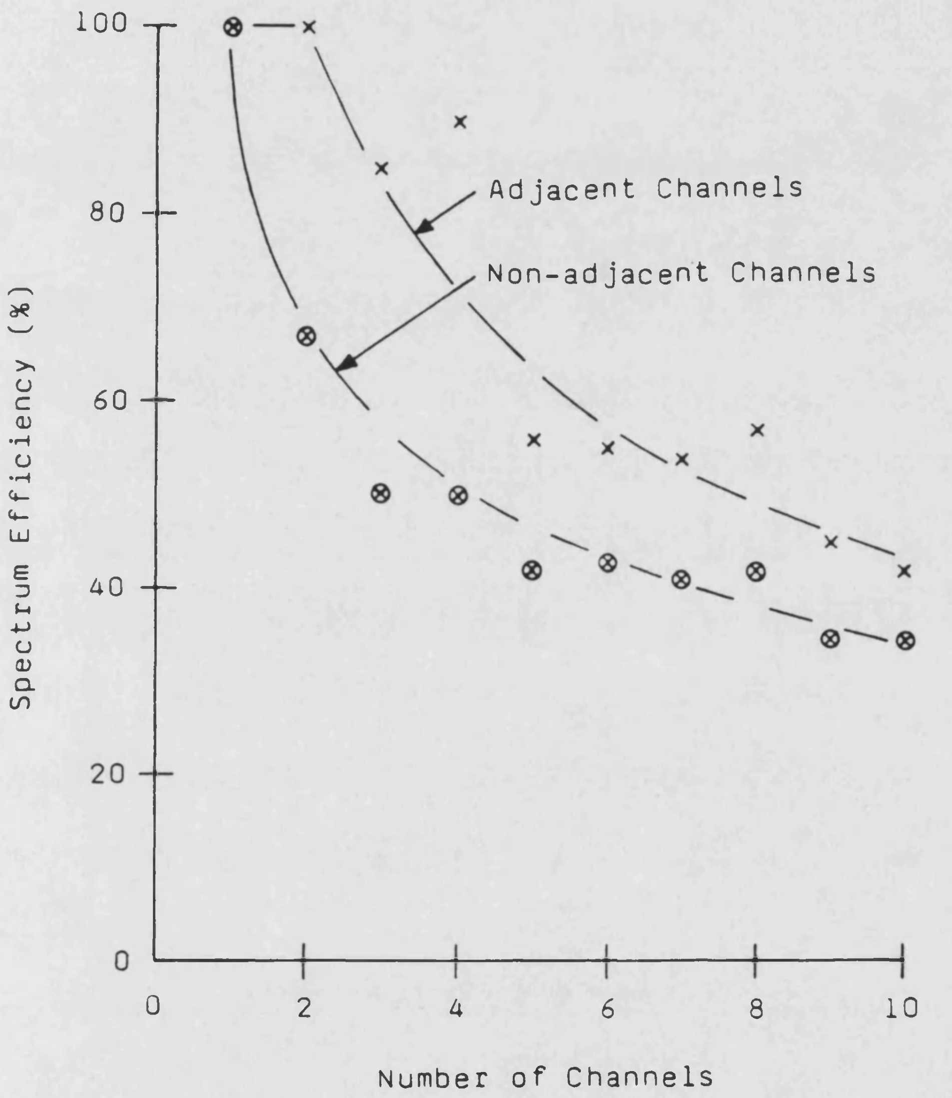

Figure 6.4. Spectrum Efficiency of 2-frequency Third Order Compatible Frequency Assignments.

third order IM, products can occupy a bandwidth three times as wide as the fundamental. This therefore can place a restriction on the spacing between acceptable channels. However, for systems which employ transmitter multi-coupling, the use of isolators and filters to protect each transmitter from all other transmitter outputs, also necessitates that channels be separated by a certain number of channel widths in order to preserve isolation, and is usually the governing factor for such in practical schemes.

It is perhaps worth noting that although a compatible frequency plan may have been assigned to a multi-channel system, it does not follow that such channels will also be compatible with the channel allocations of the other communal systems. To obtain a frequency plan which is compatible with all other systems on the site necessitates the analysis of the assignment on an individualistic basis bearing in mind all other previous channel allocations.

6.3 CHANNEL ASSIGNMENT STRATEGIES FOR CELLULAR MOBILE RADIO SYSTEMS

Frequency assignment procedures for cellular mobile schemes can be somewhat simplified by taking advantage of the inherent selective calling nature of such systems. Since the mute on a receiver will not 'lift' under solely interference inputs but only when correctly addressed, the annoyance of unwanted audio outputs due to IM products is removed. Although such on-channel interference may be present whilst a call is in progress, the likelihood of these being of sufficient strength in relation to the wanted signal to cause significant interference is generally remote. Thus, it is often said that IM compatibility in frequency assignments for cellular systems is not required, hence making channel plans for such schemes much easier.

Several different channel assignment strategies have been proposed for cellular systems. These consist of fixed frequency assignments, dynamic frequency assignments and hybrid frequency assignments [(7),(8)]. In fixed channel procedures the available channels are divided up into a number of sets, usually equal to the cell cluster size being used, and one set is permanently assigned to serve a certain cell. Only channels from this set can be used to serve a call within this cell, and these channel sets are re-used in cells separated by the re-use distance. Dynamic channel assignments differ in that all the channels are kept in a central pool, and any channels can be used in any cell. Channels are assigned to serve calls as the need arises, and the exact channel allocated to support a call depends on the state of the system (channel usage at the time a call is set up) and an assignment strategy that attempts to optimise some system parameter within the channel re-use constraint. Hybrid frequency schemes consist of a combination of both fixed and dynamic assignment procedures. The total number of channels available to the system is divided up into two groups. One group contains frequencies which are allocated using a fixed channel assignment scheme, whilst the other has channels which are allotted under a dynamic assignment procedure. Procedures involving dynamic frequency assignment schemes have the potential to match channel availability with channel requirement on a real time basis, and hence can offer a higher system efficiency. However, such procedures are understandably accompanied by added system complexity, and as such are not considered practical for present cellular systems.

A non-compatible fixed channel assignment procedure can be readily achieved in cellular systems as indicated in Table 6.1 which shows the presently adopted assignment techniques for 4-, 7-, and 9-cell cluster patterns. This type of assignment enables all available channels to be used, and since increased channel availability results in improved efficiency of a cellular system, permits maximum system efficiency to be reached from the channel assignment point of view. Such frequency assignments also generate channels that are not only equi-spaced but also maximally spaced, thus minimising the performance requirements of base station transmitter multi-coupling components.

Clearly then, IM products do not appear to cause any significant problems to the operation of cellular systems in which all base stations transmit at full power under all circumstances. However, the previous chapter has demonstrated high desirability for employing base station transmitter power control in this type of system. Unfortunately, the use of such power control with the present non-compatible channel assignments introduces conditions under which mobile receivers may suffer unacceptable levels of IM interference. These situations fall into two basic categories, those associated with the base station site, and those associated

Cell	Allocated Channel Numbers				
A	1	5	9	13	...
B	2	6	10	14	...
C	3	7	11	15	...
D	4	8	12	16	...

(a)

Cell	Allocated Channel Numbers				
A	1	8	15	22	...
B	2	9	16	23	...
C	3	10	17	24	...
D	4	11	18	25	...
E	5	12	19	26	...
F	6	13	20	27	...
G	7	14	21	28	...

(b)

Cell	Allocated Channel Numbers				
A	1	10	19	28	...
B	2	11	20	29	...
C	3	12	21	30	...
D	4	13	22	31	...
E	5	14	23	32	...
F	6	15	24	33	...
G	7	16	25	34	...
H	8	17	26	35	...
I	9	18	27	36	...

(c)

Table 6.1. Typical Non-compatible Channel Assignments
(a) 4-cell Cluster, (b) 7-cell Cluster,
(c) 9-cell Cluster.

with mobiles.

At the cell site the usual problems of co-siting many transmitters exist in that IM is generated by direct transmitter interactions and by the 'rusty bolt' effect. If we assume that the transmit power range for base stations is the same as that specified in TACS for mobiles, then the variation in output power will extend over a total of 32dB. A 'worst case' scenario may be envisaged in which a mobile, close enough to its base station to require only minimum transmit levels, is operating on a channel which bears a third order IM relationship with other base station transmitters at the same site which are operating at full power in order to maintain contact with mobiles at the cell periphery. Assuming that the mobile receiver close to the base station requires a protection ratio of 8dB, a generally accepted figure for 25kHz FM channels [9], then the offending third order product must be at least 40dB down on full power emissions. This suggests a need for some 33dB of isolation between base station transmitters [10], and although a relatively modest requirement in general multi-coupling terms, will impose restrictions on the minimum frequency separation of the transmitters.

For mobiles a somewhat different problem exists. Since mobile receivers are required to operate on all system channels they are consequently wideband and therefore exposed to whatever emissions are operating locally. Published data indicates that under conditions of maximum sensitivity, ie. an input signal of 0.5μV p.d. (-113dBm), the dynamic range of currently available mobile equipment is some 65dB. Thus a third order IM product on a wanted channel is discernible when the signals which produce it are 65dB above the wanted signal level of -113dBm, ie. -48dBm. For input signals above this level, third order products can increase by up to 9dB for every doubling of unwanted signal power, assuming they increase together, or by 6dB if only one increases [11]. Returning to the 'worst case' scenario cited previously, if the 'victim' mobile, ie. the one close to the cell site, is not to suffer from IM interference then, if the wanted signal is transmitted 32dB below maximum effective radiated power (ERP), which in present systems is approximately 100W, it can easily be shown that the path loss from base station to mobile must be in excess of 85.5dB. This tends to suggest an area around cell sites of some 500 metres in radius within which operations would be potentially receiver non-linearity limited if the 8dB protection ratio previously mentioned is to be maintained. As a consequence, such receiver generated IM is likely to dominate any effects associated with products generated at the cell site.

If base station power control is to be implemented then it can be seen that either a very substantial improvement in mobile receiver linearity must be achieved, or third order compatible frequency assignment strategies must be followed. Since base station transmitters are relatively few in number compared to the expected number of mobiles, the most cost effective approach must be the latter. However, the practicality of performing such assignments in an optimum manner has, up to now, been uncertain.

6.4 IMPLEMENTATION OF THIRD ORDER COMPATIBLE CHANNEL ASSIGNMENTS IN CELLULAR SYSTEMS

It is evident from the preceding discussion that unless third order IM compatibility can be achieved in cellular system channel assignments, then base station transmitter power control may well leave mobiles close to cell sites vulnerable to receiver generated interference due to the presence of high level emissions on other channels at the same site. When considering this requirement for IM free frequencies, two questions clearly emerge.

(1) Given the number of channels available to a system and the cell cluster size as parameters, can assignments be produced which are efficient in that they maximise the number of channels used from the total number of available channels, while maintaining third order compatibility.

(2) Can such frequency plans be achieved in which the separation between channels operating from the same site is sufficient from the point of view of practical multi-coupling components.

Procedures for generating third order IM free assignments for conventional LMR systems have concerned themselves with obtaining a set of compatible frequencies from the minimum necessary number of total channels. The requirement of cellular systems is similar except that instead of obtaining just a single set of frequencies, several sets of compatible channels must be provided, the exact number of sets required clearly depending on the cell cluster configuration being implemented. Obviously, one method of obtaining several channel sets would be to use these existing procedures in an iterative manner thus generating each set of frequencies separately. This would ensure IM compatibility and could be arranged so as to satisfy multi-coupling requirements. However, it is obvious that this approach is by no means optimum since it would demand an unprecedented number of channels from which to choose, and would consequently result in an extremely low overall spectrum efficiency. Thus, an alternative approach must be sought and adopted which not only provides third order compatibility with sufficient channel separation, but considers the assignment of all frequency sets simultaneously, thus enabling such allocations to be made from the minimum number of total channels.

Although the concept of optimal IM compatible channel assignment for cellular systems is simple, the generation of such frequency plans is far from it. An optimal channel assignment ie. one that minimises the number of channels needed, is, unfortunately an NP-complete problem [12], (a problem for which no polynomial time algorithm is known [13],[14]) and hence a procedure for generating such an assignment will almost certainly necessitate the use of computational techniques. An initial investigation into the efficiencies of such frequency plans has already been carried out by Gardiner and Kotsopoulos [15]. Using a simple recursion formula for generating two-frequency third order compatible lists [4], the average number of channels per cell for 4-, 7-, and 12-cell cluster sizes have been calculated for various minimum channel separations given the total number of channels available. The resulting efficiencies of these assignments show that compatibility may well be achievable in cellular systems under certain conditions without a significant decrease in the total number of assigned channels. Unfortunately, only average values of the number of channels assigned per cell are mentioned in these calculations, with no indication being given as to the exact number of channels in each cell. As a result, it is believed that such efficiencies are only obtainable with a highly non-uniform distribution of channels per cell. Although situations undoubtedly arise in which certain cells within a cluster require more channels than others, in urban areas the assignment of channels to cells within the same cluster is required to be more uniform. Thus knowledge of the efficiency of IM compatible assignments under these conditions is also required if the introduction of such frequency plans is to be seriously considered.

The problem of compatible frequency assignments in cellular systems can be observed to consist of two distinct parts. Firstly, the generation of sets of IM compatible channels, as for conventional systems, but in a manner that satisfies the parameters and constraints of cellular schemes. And secondly, the combination of the relevant number of these sets to form suitably sized groups of channel sets, within which no channel appears more than once. Using this as a basis, computer programs have been written which enable optimal third order IM compatible channel plans to be produced for cellular schemes where an equal number of channels is required to be assigned to each cell within a cluster. Listings of these programs, complete with comments to aid understanding are given in appendix A on page 283 of this thesis. Despite optimisation of the programs, analysis of large cell clusters proved difficult with the computing power available and so concentration has been focused on the smaller cellular patterns of 4-, 7-, and 9-cells per cluster.

The results obtained from the analysis of 4-, 7-, and 9-cell clusters to the implementation of optimal third order IM compatible channel assignments are presented in Figures 6.5 to 6.16. Figures 6.5 and 6.6 show the minimum number of consecutive channels required for such assignments for a 4-cell cluster pattern for the case of 2-frequency and complete third order compatibility respectively, for several values of minimum channel separation. Figures 6.7 and 6.8 show the corresponding spectrum efficiencies of these channel assignments. Similarly, Figures 6.9 to 6.12, and Figures 6.13 to 6.16 show the performance of 7- and 9-cell clusters under the same conditions.

The characteristics that emerge from this analysis of optimal third order IM compatible channel assignments for cellular systems can be summarised as follows;

(1) The assignment efficiency of these allocations, as might be expected, increases as the minimum permissible spacing between co-sited channels is reduced.

(2) Increasing the number of channels required per cell causes the efficiency of such assignments to

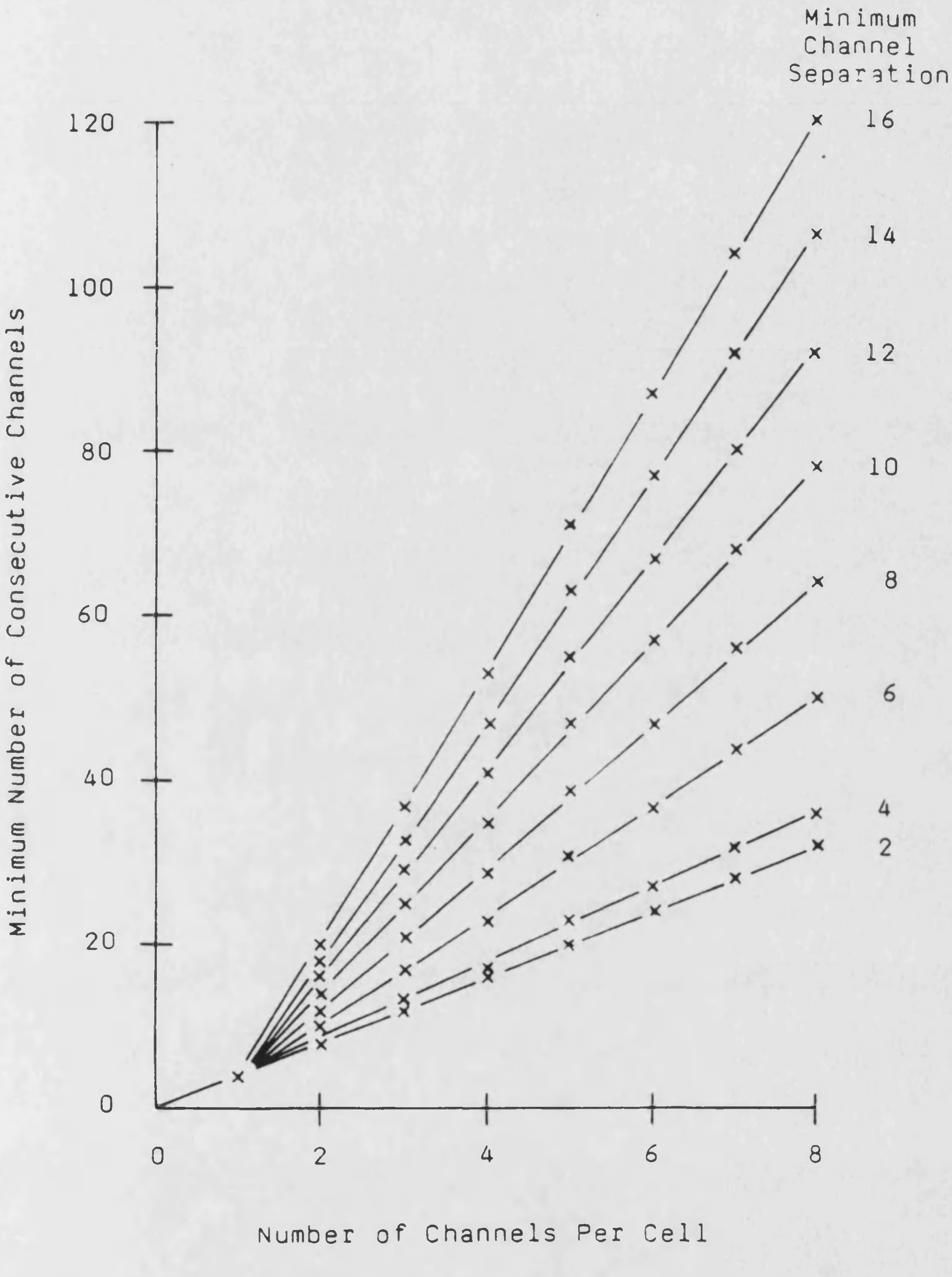

Figure 6.5. Channel Requirements for 2-frequency Third Order Intermodulation Compatibility for a 4-cell Cluster Pattern.

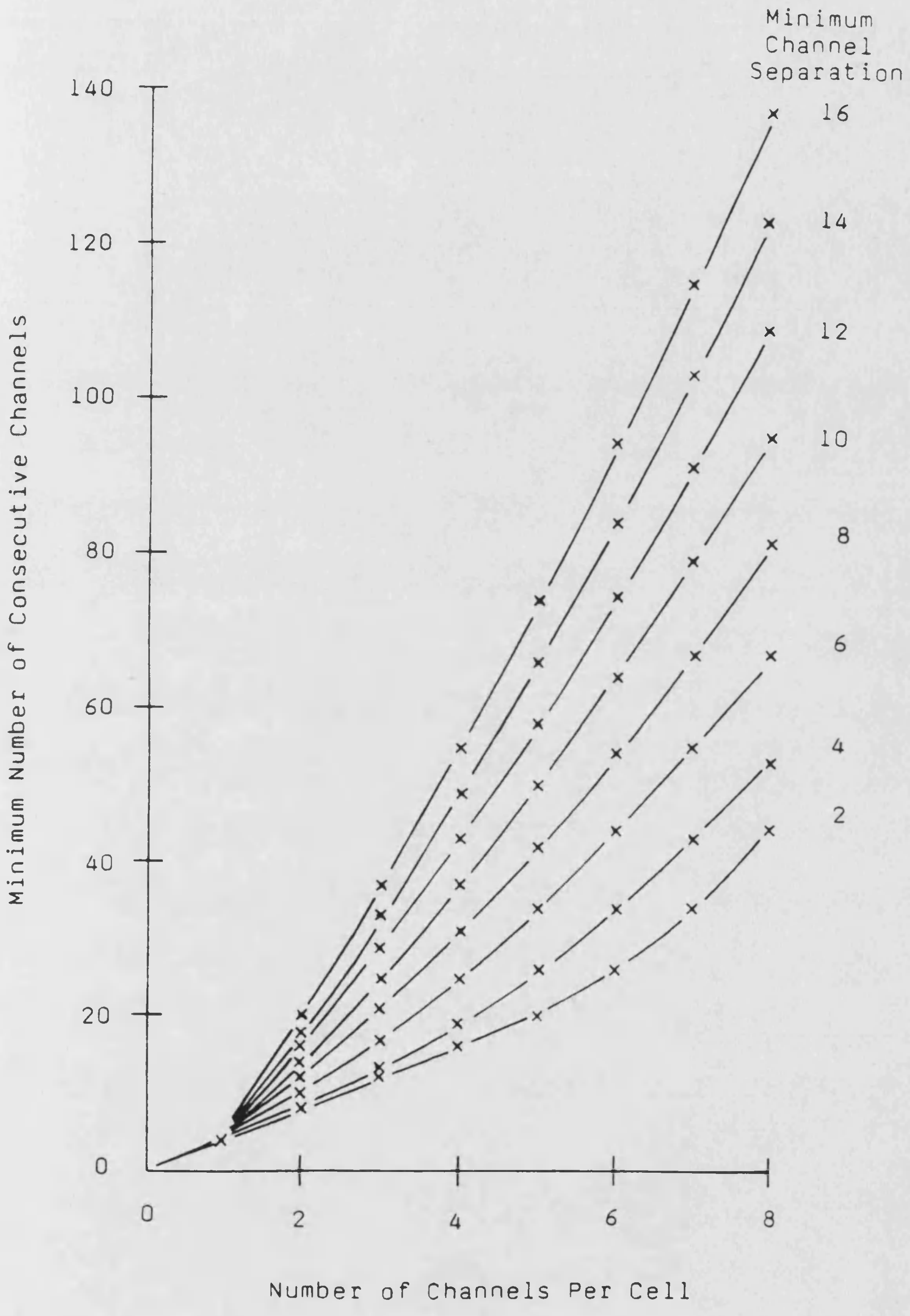

Figure 6.6. Channel Requirements for Complete Third Order Intermodulation Compatibility for a 4-cell Cluster Pattern.

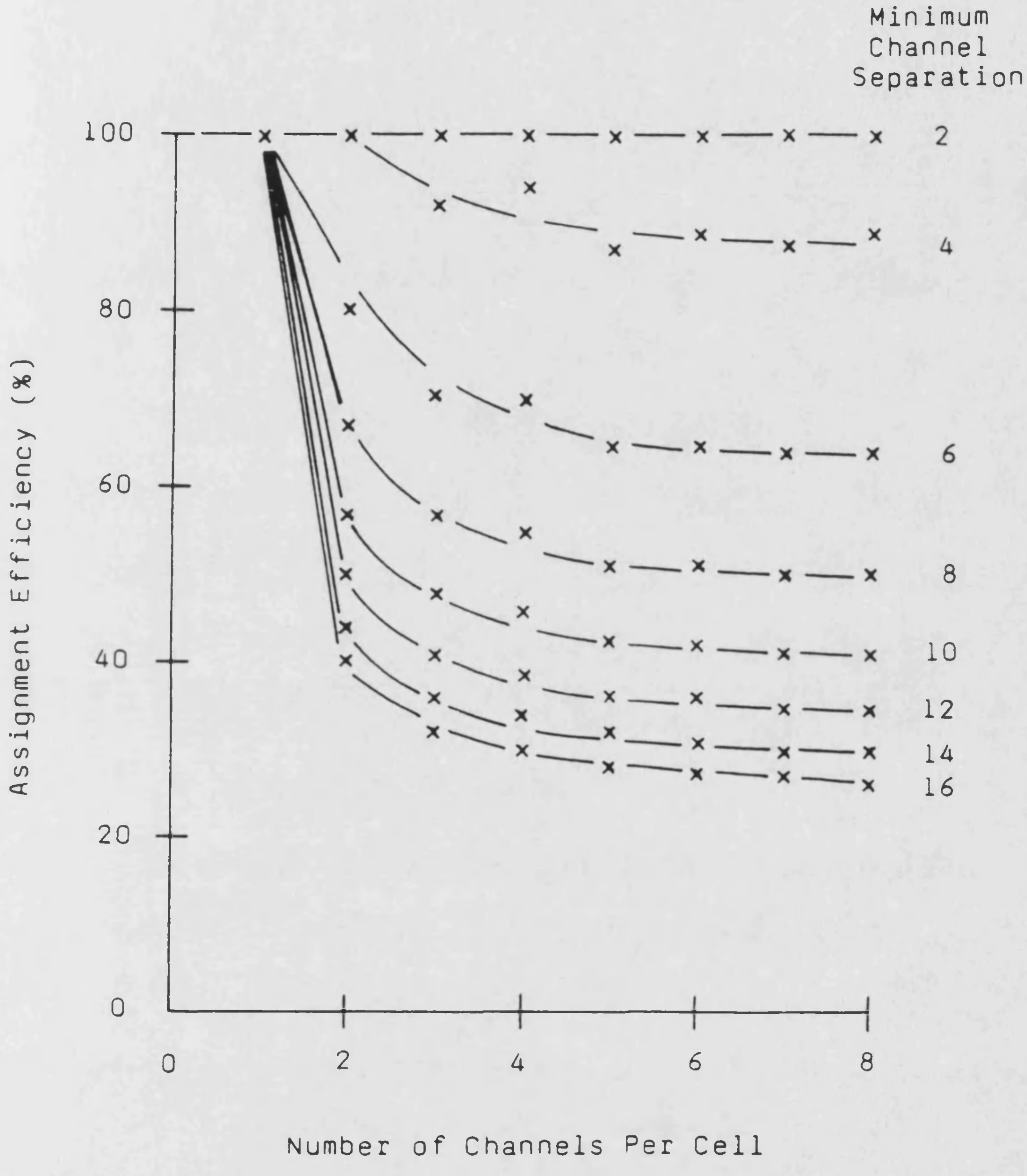

Figure 6.7. Spectrum Efficiency of 2-frequency Third Order Intermodulation Compatible Channel Assignments for a 4-cell Cluster Pattern.

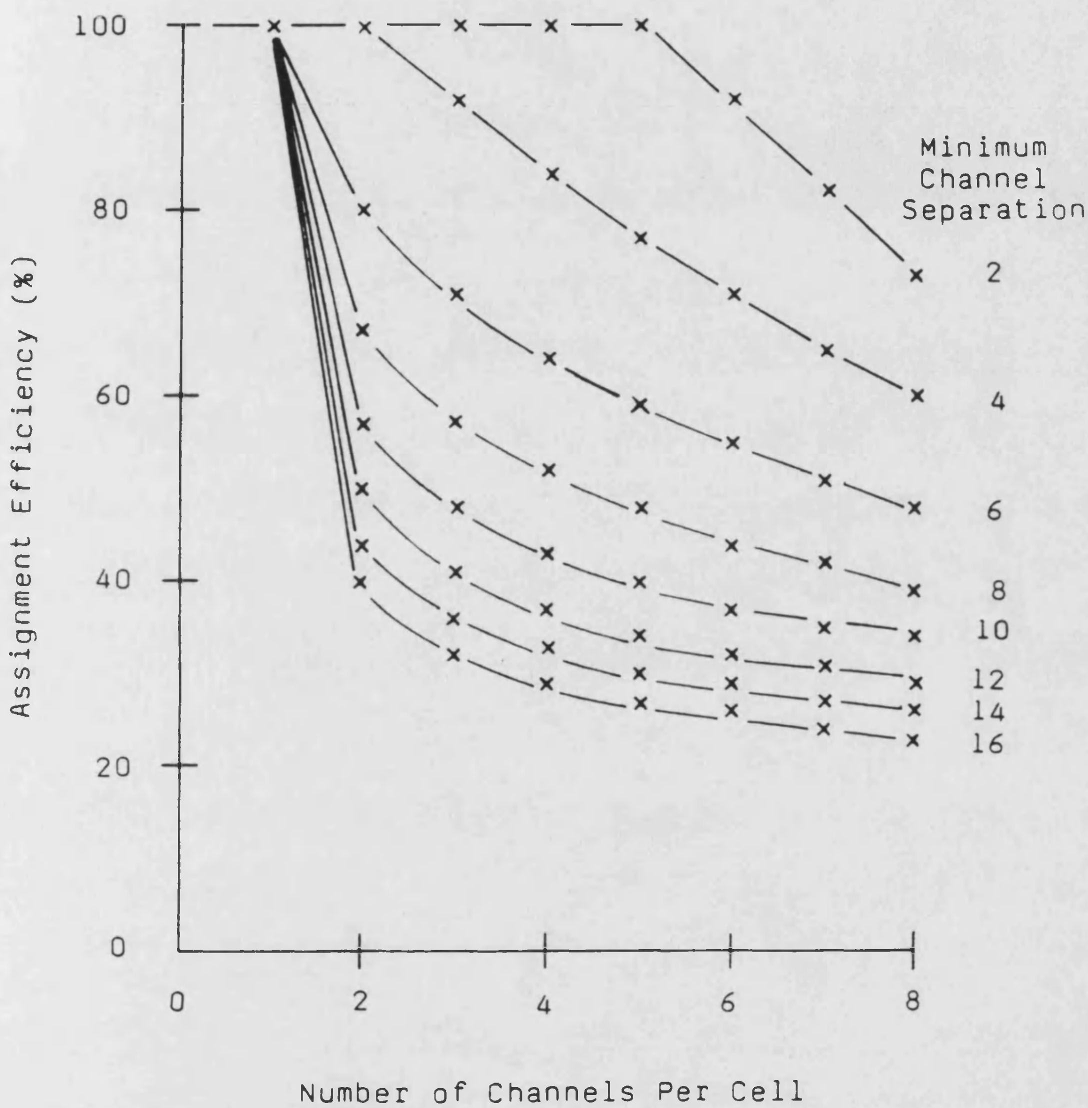

Figure 6.8. Spectrum Efficiency of Complete Third Order Intermodulation Compatible Channel Assignments for a 4-cell Cluster Pattern.

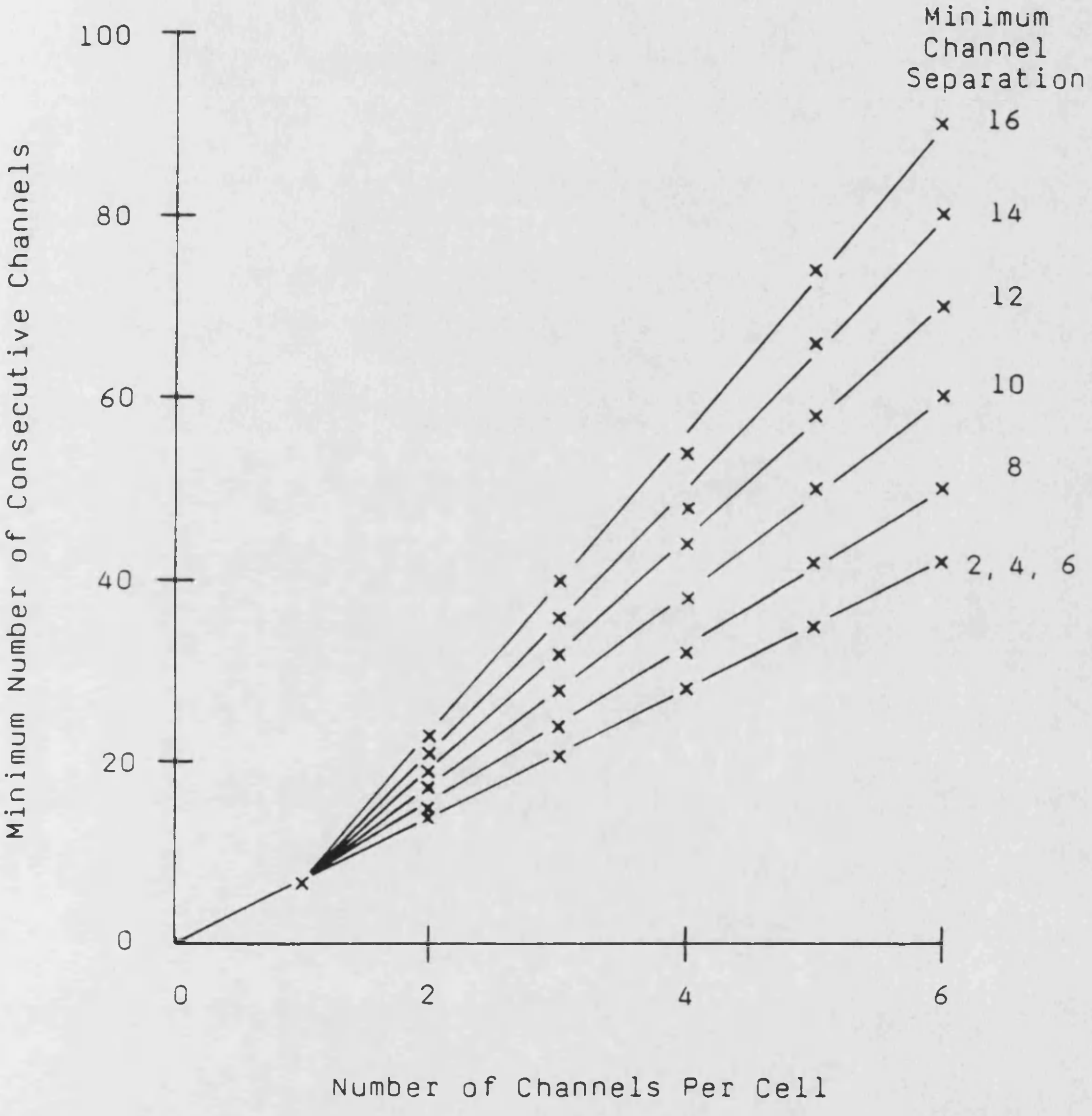

Figure 6.9. Channel Requirements for 2-frequency Third Order Intermodulation Compatibility for a 7-cell Cluster Pattern.

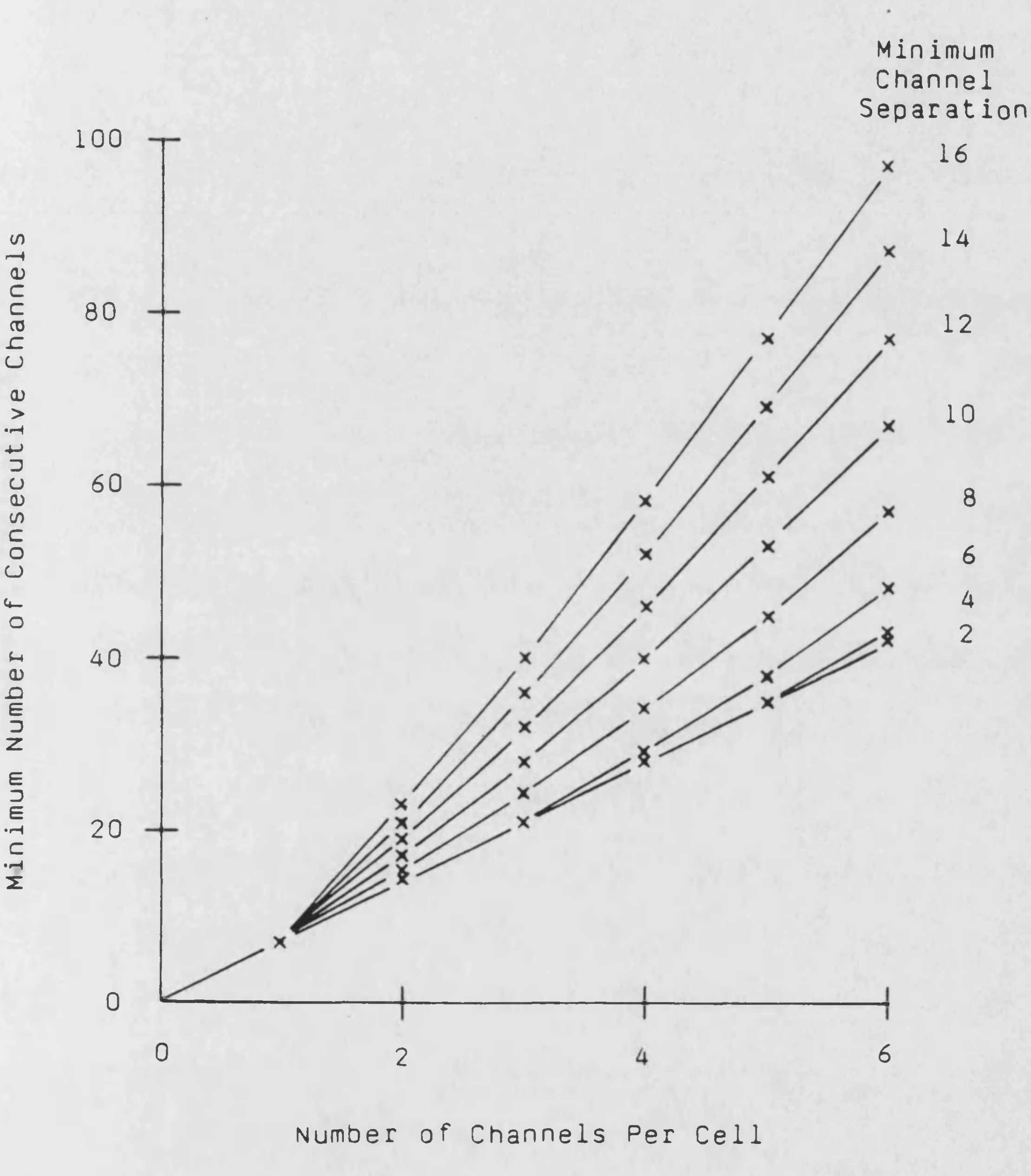

Figure 6.10. Channel Requirements for Complete Third Order Intermodulation Compatibility for a 7-cell Cluster Pattern.

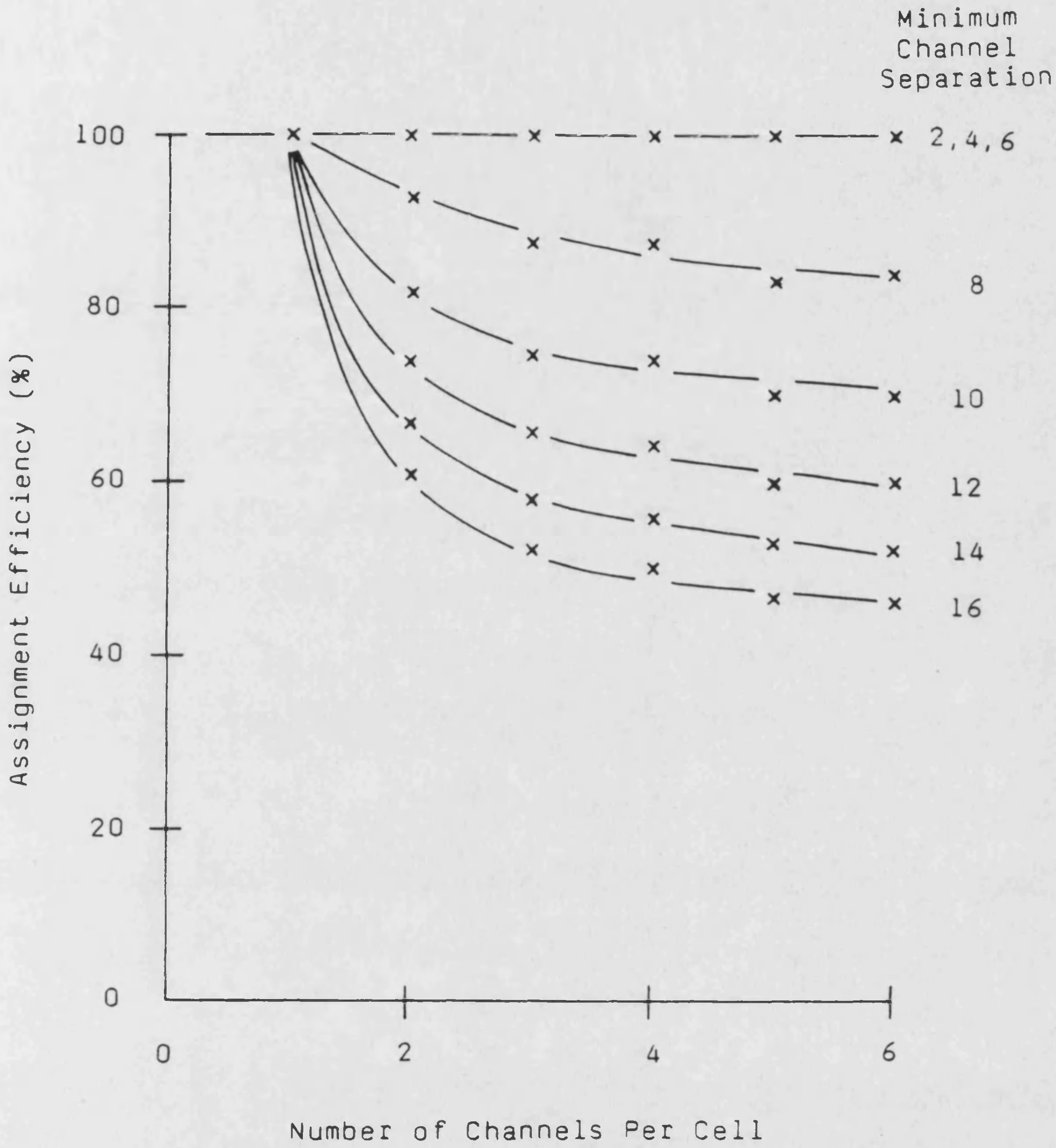

Figure 6.11. Spectrum Efficiency of 2-frequency Third Order Intermodulation Compatible Channel Assignments for a 7-cell Cluster Pattern.

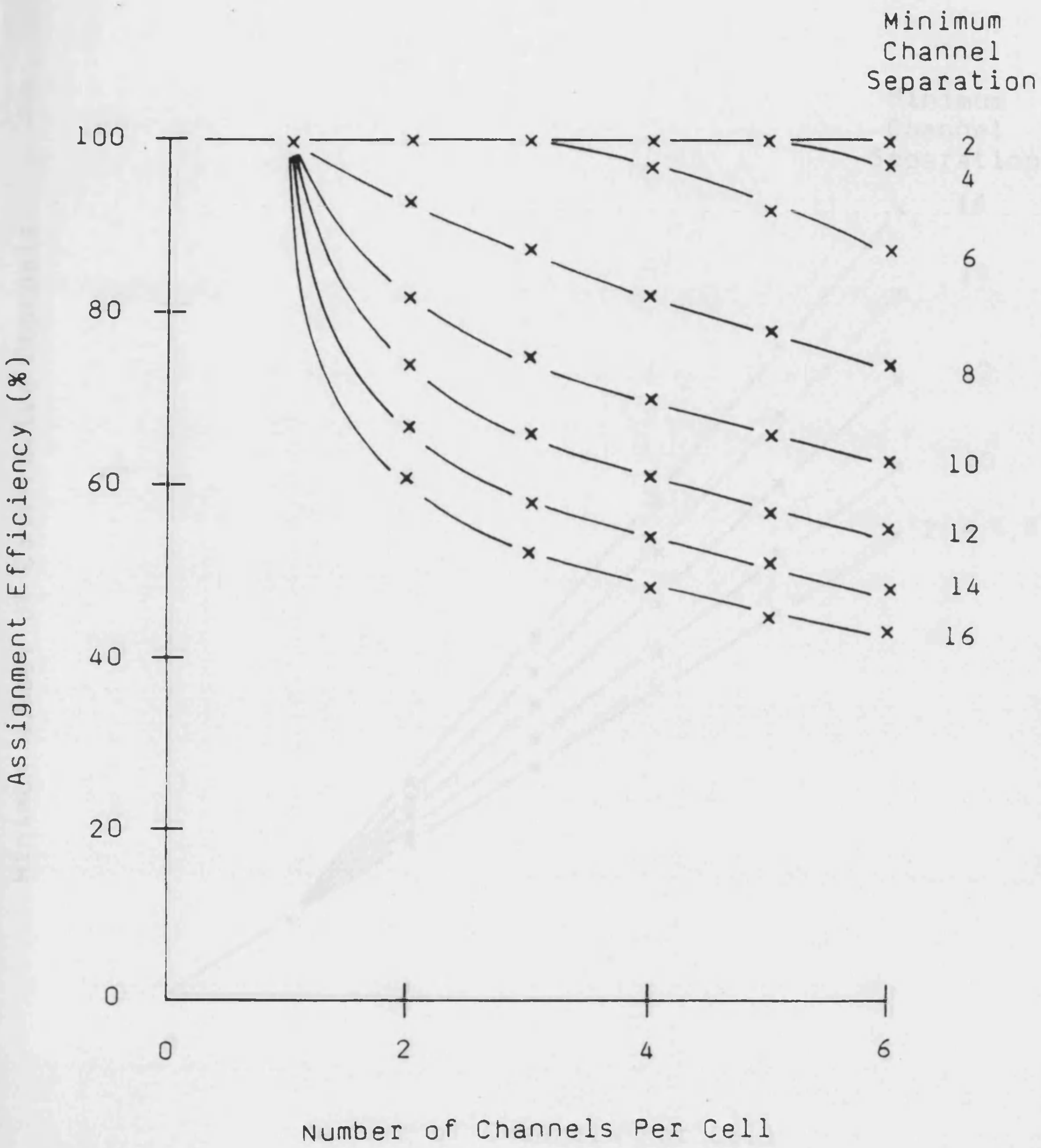

Figure 6.12. Spectrum Efficiency of Complete Third Order Intermodulation Compatible Channel Assignments for a 7-cell Cluster Pattern.

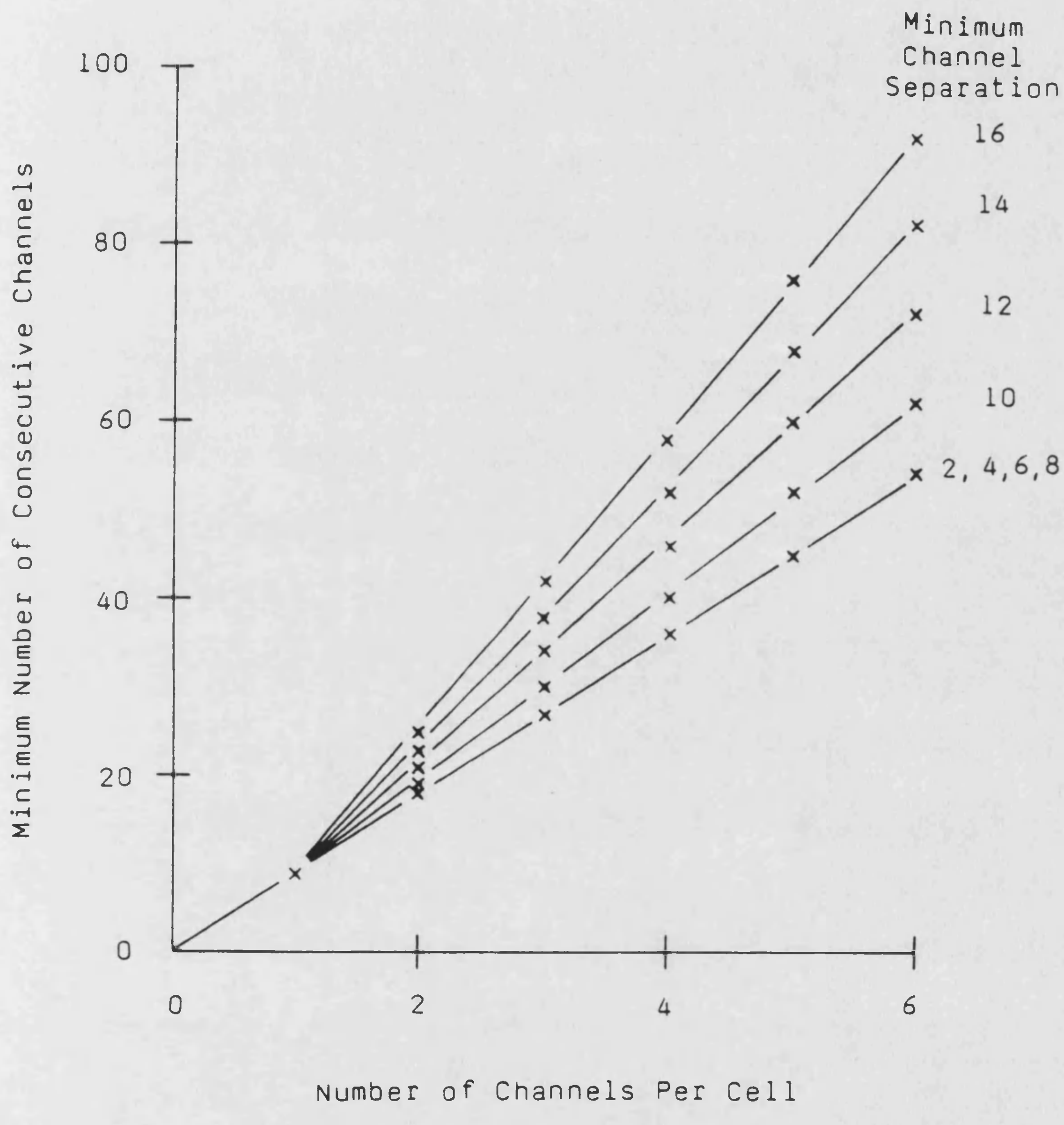

Figure 6.13. Channel Requirements for 2-frequency Third Order Intermodulation Compatibility for a 9-cell Cluster Pattern.

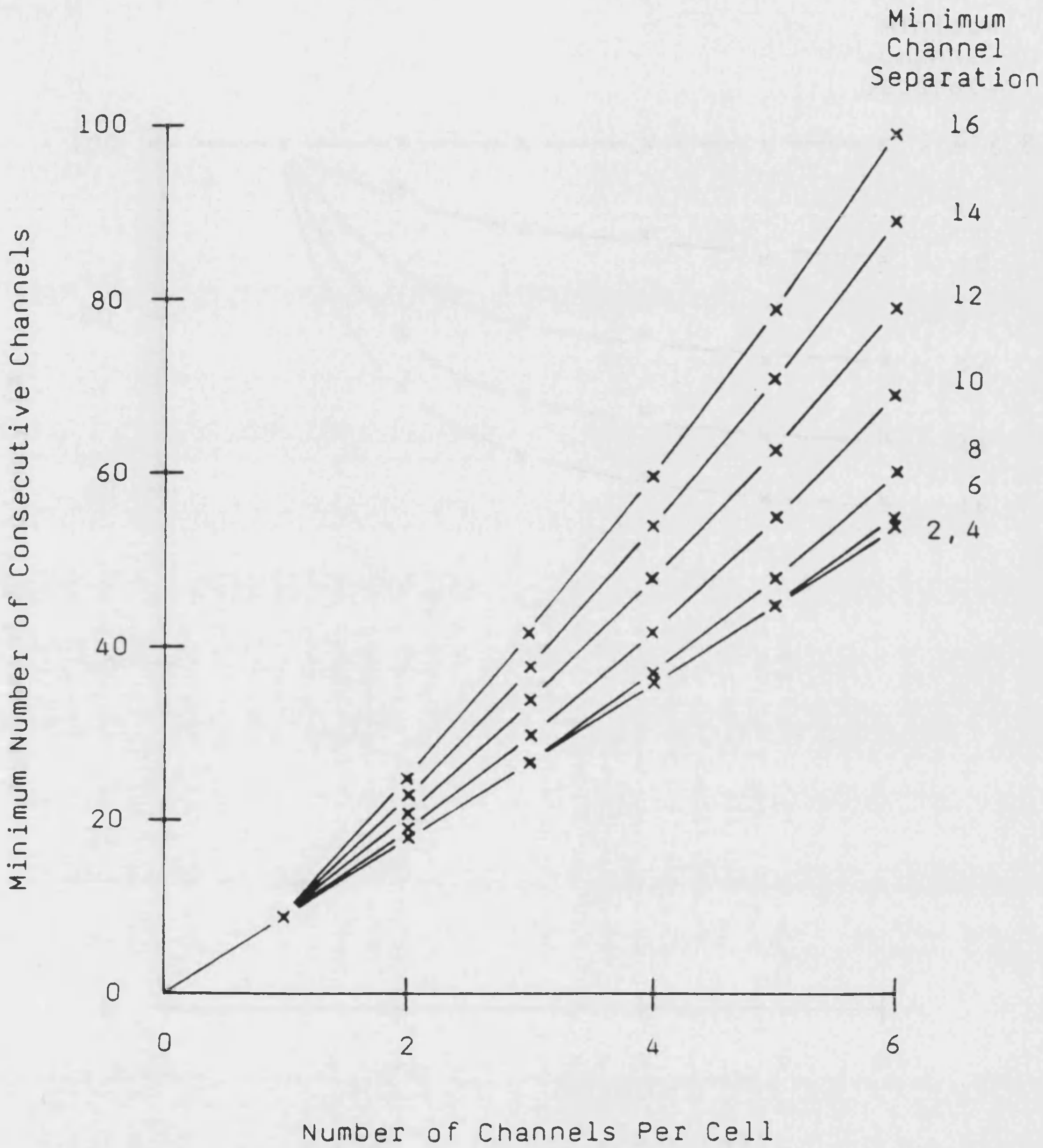

Figure 6.14. Channel Requirements for Complete Third Order Intermodulation Compatibility for a 9-cell Cluster Pattern.

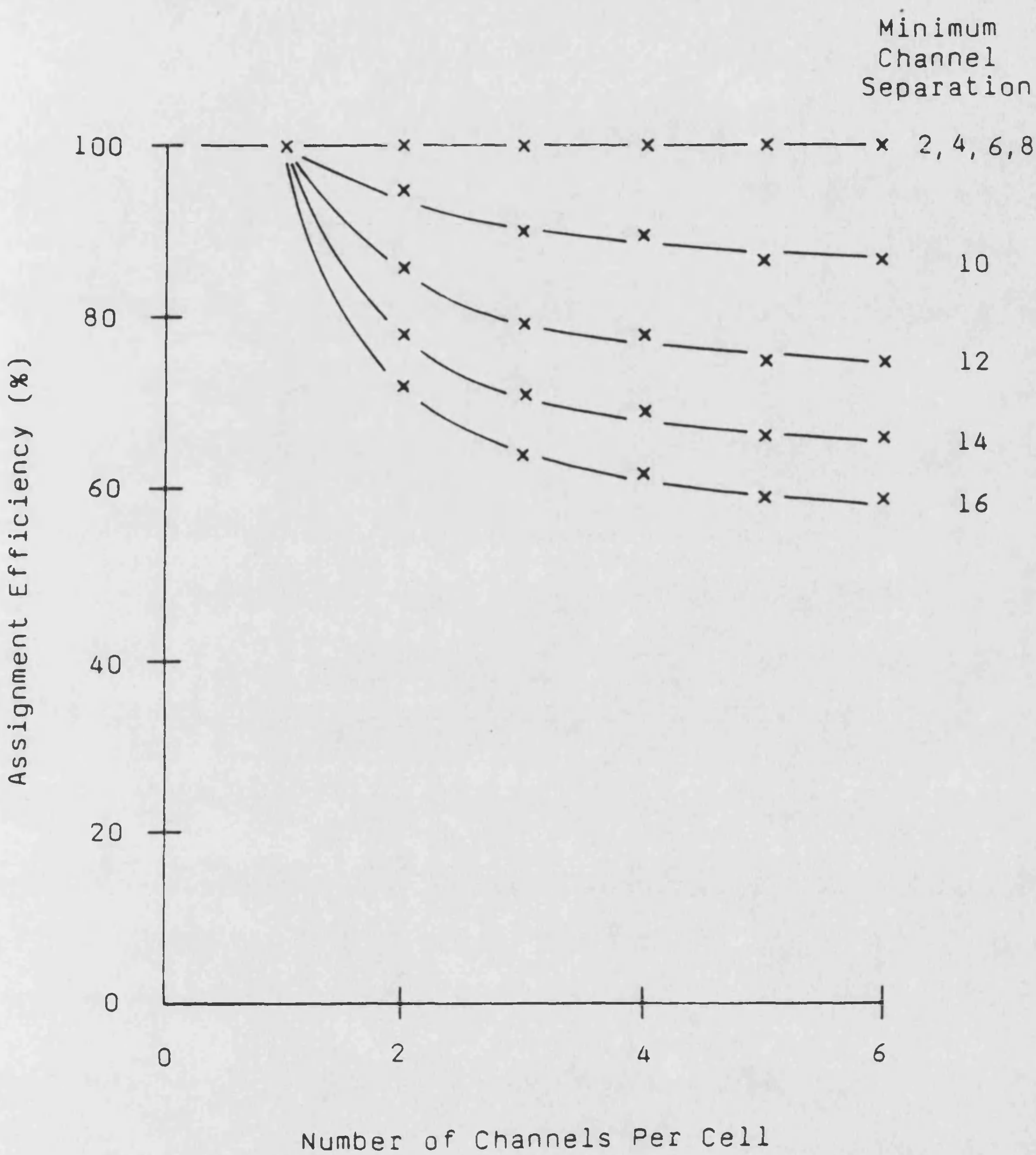

Figure 6.15. Spectrum Efficiency of 2-frequency Third Order Intermodulation Compatible Channel Assignments for a 9-cell Cluster Pattern.

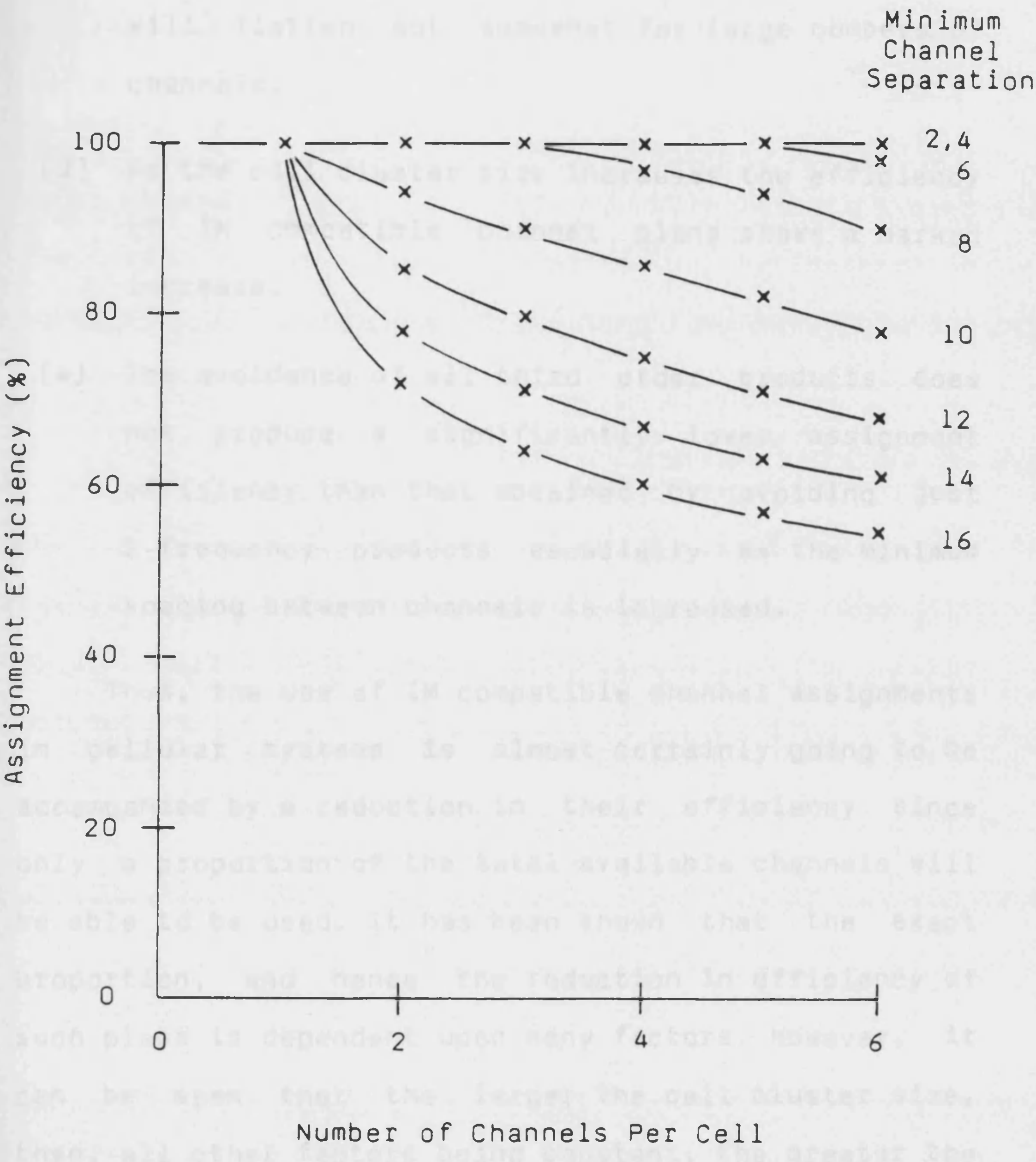

Figure 6.16. Spectrum Efficiency of Complete Third Order Intermodulation Compatible Channel Assignments for a 9-cell Cluster Pattern.

fall, but there is every indication that this will flatten out somewhat for large numbers of channels.

(3) As the cell cluster size increases the efficiency of IM compatible channel plans shows a marked increase.

(4) The avoidance of all third order products does not produce a significantly lower assignment efficiency than that obtained by avoiding just 2-frequency products especially as the minimum spacing between channels is increased.

Thus, the use of IM compatible channel assignments in cellular systems is almost certainly going to be accompanied by a reduction in their efficiency since only a proportion of the total available channels will be able to be used. It has been shown that the exact proportion, and hence the reduction in efficiency of such plans is dependent upon many factors. However, it can be seen that the larger the cell cluster size, then, all other factors being constant, the greater the efficiency of these assignments. Hence, the implementation of this type of frequency plan suggests the use of cell clusters larger than the presently adopted size for TACS of seven. However, the already discussed inherent disadvantages of using larger cell patterns must be remembered. As with most aspects of mobile radio systems, there appears to be no clear cut decision. The introduction of compatible channel assignments seems to be in conflict with other system requirements. However, if co-channel interference is to be kept to a sensible level, then the implementation of power control may be the only course of action available. As to whether or not this is accompanied by a change in the channel assignment strategy for cellular schemes is a matter for further research, since the introduction of such a procedure will almost undoubtably result in a trade-off situation with other system parameters.

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CHAPTER SEVEN

ASPECTS OF BASE STATION POWER CONTROL IMPLEMENTATION

7.1 INTRODUCTION

In mobile radio systems, base station transmitter powers are pre-selected so as to ensure a satisfactory level of communication exists throughout their entire service area. The use of high powers can enable this criterion to be met, but from a spectrum conservation point of view, it is important that transmitter powers are limited to the minimum necessary level to provide the communication quality. Although this is true for all LMR schemes, it is especially so for cellular type systems, where the employment of frequency re-use on a small geographic scale makes them very vulnerable to co-channel interference. Obviously, it is the requirement to provide an adequate level of communication right up to the boundary of a base station's service area that ultimately governs the transmitter powers that have to be used in a scheme. However, for a large part of the time, mobiles are located much closer to the base station, and hence receive a stronger signal than is necessary to provide adequate communication quality.

The use of a control scheme whereby the base station transmitter power can be varied in accordance with the transmission characteristics present between mobile and base station can enable the output level to always be maintained at the lowest possible level consistent with the required grade of service irrespective of the mobile's position. As a consequence, co-channel interference levels for other mobiles can be reduced, thus raising the overall level of communication quality within the system.

In duplex radio systems, the ability to perform simultaneous transmission and reception would enable base station output power levels to be altered during the course of the call. For simplex systems, such power control would obviously not be possible. The relevant base station power level for the next period of transmission would have to be set during the interleaving mobile transmit period, based on the signal quality received at the mobile during the previous base station transmission period. Although this would limit the extent to which the base station output power and mobile received signal quality could be matched, the relatively short transmission periods generally used over simplex schemes would still enable a relatively close degree of power control to be achieved, and the benefits of such control to be gained.

This chapter considers the implementation aspects of a base station power control system. For systems already possessing mobile power control the practicality and limitations of using reciprocity to perform base station power control are discussed. The three distinct requirements of a base station power control scheme are identified and the practical implementation of each aspect examined in turn as regards possible methods of accomplishment and the corresponding implications.

7.2 IMPLEMENTATION REQUIREMENTS OF A BASE STATION POWER CONTROL SYSTEM

The first requirement that is immediately apparent for an LMR base station power control system is that such a scheme must be completely automatic in operation. Since there is no direct knowledge at the base station as to the quality of the signal being received at the mobile, then obviously an assessment of signal quality will have to be made at the mobile and the information relayed back to the base station as to the required change in base station output power. Although this is the case for most LMR schemes, the use of mobile transmitter power control in current cellular systems means that cellular base stations already possess a certain degree of knowledge about the transmission characteristics between mobile and base station. If reciprocal propagation is assumed to exist, then the base station output power could be adjusted in an identical manner to that of the mobile, thus effecting both base station and mobile transmitter power control through the use of the already installed mobile power control system. Implementing base station power control by this method would obviously be the simplest and most straightforward way possible for cellular schemes, although for other LMR systems not yet equipped with any form of mobile power control, the introduction of base station power control would be somewhat more involved requiring the installation of a dedicated base station power control system.

Implementation of a base station power control scheme on a reciprocal propagation basis, would however, restrict the operation of the base station power control to the same discrete nature as that invariably used in current cellular systems to perform the mobile power control function. Since the main function of a mobile power control scheme is to prevent desensitisation, and hence intermodulation occurring, in the base station distribution amplifier, then the use of a power control system in which the mobile power is reduced in a series of steps of pre-determined magnitude enables this aim to be achieved satisfactorily. However, for base station power control, the aim of reducing co-channel interference levels could perhaps benefit from a more stringent form of power control, and hence would require its own separate control system. Also, the use of diversity techniques for base station reception, together with the lower levels of noise and man-made interference that are generally found around a base station site, and the variable performance characteristics of differing mobile equipment could all lead to the operation of a power control system working on reciprocity to be somewhat suspect.

The practical implementation of a base station power control system can be seen to consist of three distinct aspects.

(1) The measurement/assessment of the mobile received signal quality.

(2) The conveyance of the signal quality/power control information between mobile and base station.

(3) The regulation of the base station power so as to provide the minimum necessary output level.

Current methods of measuring/assessing the quality of a received signal operate either within the IF stages of the receiver or directly on the audio output of the demodulator. In FM systems, a measurement of the strength of a received signal can provide a simple but effective indication as to the quality of the demodulated baseband signal. For a mobile receiver structure, a dc voltage level can easily be obtained from within the IF strip as to the received signal level and hence the corresponding received signal quality. A detected voltage exceeding a prescribed level equivalent to the required quality would therefore indicate that the transmitter power of the base station was too high and a reduction in output level could be tolerated. Conversely, a dc voltage below this prescribed level would imply the presence of an inferior quality signal and correspond to a request for an increase in the output power of the base station.

Unfortunately, signal strength measurement techniques operate by measuring the total energy contained within the received radio channel. As a consequence, there is no way of distinguishing between the wanted signal and other in-band signals such as noise and interference. A specific signal strength level can therefore be solely caused by the wanted signal or due to both the wanted signal and other interference effects. The technique offers no distinction between the two situations, although the signal quality of the latter will be understandably inferior to that of the former, and so is not certain to always give a true representation of the received signal quality.

The use of more complex techniques can however make the distinction between the two conditions, and hence can enable a true signal quality measurement to be performed. The use of phase perturbations imposed on low level pilot tones by propagation and interference effects is a simple concept that has been used to enable real time signal quality estimation to be performed [1],[2],[3]. The use of one or more tones located at natural or artificially made nulls within the baseband spectrum permit a signal quality measurement to be performed at either a spot frequency in the baseband signal, or over a range of frequencies within the audio bandwidth, thus enabling an accurate assessment even when non-uniformly distributed interference is present. A comparison between the zero crossings of the perturbed pilot tone signals and locally generated reference signals can provide a direct measurement as to the quality of the pilot tone signals and hence a measure of the overall received signal quality.

In a similar manner, another technique that can be used to assess signal quality directly is that of using a set of tones of equal amplitude and random phase to constitute a baseband signal [4]. Setting one or more of these amplitudes to zero prior to transmission forms slots within which, any power that exists at the receiving end will be solely due to noise, distortion, or interference effects encountered by the signal during processing and propagation. A comparison between the amplitude of the received signal at the tone frequencies and that at the slot frequencies can be interpolated as a direct measurement of the received signal quality [4]. The use of such a technique obviously requires the temporary suspension of normal audio transmission, and as such, limits the duration and repetition of signal quality measurements, and hence power changes.

Although the aim of a base station power control system is to maintain the required communications quality at the mobile whilst using the minimum necessary transmitter output power, a control system based on a true signal quality assessment technique could be potentially dangerous. For instance, for a base station power control system using signal strength as the basis on which to adjust the transmitter power, in the unfortunate circumstances of a mobile experiencing a good deal of on-channel noise and interference, the signal strength would be deceptively high for the quality of the signal being received. As a consequence, the mobile would suffer from a communications quality below that which the system aims to achieve. However, in a power control scheme based on a true signal quality measurement technique, a mobile in an identical situation would request an increase in the output power of the base station in order to overcome the level of interference. As a result, other co-channel mobiles could then find themselves in a similar position to the first mobile, suffering from too high a level of interference, and they also would then request a power level increase. The situation can easily be seen to be developing into a 'power race', the outcome of which could well be that all base station transmitters end up using maximum output power in order to try to provide the required signal quality at their respective mobiles. The condition of one mobile receiving a lower signal quality than that planed for the system could thus cause the entire power control system to collapse and hence for all the mobiles to suffer the same high levels of interference as experienced prior to the introduction of base station power control. Obviously, such a condition must be avoided and so it seems unlikely that a base station power control system will ever be able to operate on true signal quality assessment alone.

The second aspect of practical implementation is that of relaying the signal quality/power control information back from the mobile to the base station. There are essentially two distinct ways in which this task can be performed, namely in a digital or analogue manner. The inability to use a separate radio channel on which to transmit the power control information dictates the requirement to convey such information along with the normal audio, and in the case of cellular systems, other signalling and supervisory signals. This therefore limits the method by which either the analogue or digital signal is transmitted to a mode which causes little, or idealy no perceptible degradation on the present audio performance of the system.

The power control information could be either frequency multiplexed in with the normal audio through the use of in-band [5] or out-of-band signalling techniques or time multiplexed in with the audio by using temporarily blanked speech [6],[7],[8] or time compression techniques [9],[10],[11]. The time multiplex method would clearly limit the power control information to being transmitted in bursts whereas the use of frequency multiplexing offers the potential to perform a continuous transmission of power control information, and hence the possibility of a closer degree of overall power control. For a digital implementation, the fact that the power control data would be transmitted along with the mobile audio and possibly other signalling/supervisory signals would, of course, restrict the rate at which power control information could be transmitted. For a system employing in-band or out-of-band digital signalling, a data rate of less than 300 baud would probably have to be used in order to meet overall bandwidth limits. Although the use of blanking or compression techniques could enable the bursts of power control data in a time multiplex type of system to be transmitted at a faster rate, the practical limitations imposed on such techniques would still give a similar relatively slow overall data rate.

An analogue power control system has the potential to use such properties as amplitude, phase or frequency as a means of conveying the power control information. The many problems associated with the use of amplitude as a means of conveying information makes its use highly suspect, and as a consequence, is very seldom used in practice. The use of phase as a method of relaying the power control message would necessitate the continuous transmission of some form of reference signal in order for the information to be correctly interpolated at the base station. The inherent difficulties of performing such a task, particularly in a mobile radio environment, would probably preclude its use too. The robust nature and inbuilt reference feature of frequency makes a power control system based on frequency seem the most likely form of analogue type system. Variations in the frequency of a tone located either outside the normal audio bandwidth or possibly within the audio band at a suitable point so as to cause no perceptible deterioration in audio performance (5), would permit a continuous control over the base station output power to be exercised. The speed at which the frequency of the tone could vary and hence the rate at which power changes could be made would obviously be governed, in a similar manner to that of the transmission of data, by overall bandwidth considerations. However, a continuous variable frequency tone system would be making less abrupt changes in frequency at a slower rate than a digital system in order to perform the power control. Hence, the use of such a technique would enable a power control system to operate at an equivalent data rate far in excess of that achievable by digital techniques in the available bandwidth.

In a similar manner to the conveyance of the power control information, the adjustment of the base station transmitter power can be performed in two distinct ways. The changes in output power could either be in a digital form through the use of discrete power levels and a series of steps of pre-defined magnitude, or of a continuously variable nature in a proportional manner linearly related to received signal quality, thus allowing any level between the pre-defined maximum and minimum limits to be selected. The use of digital techniques in relaying the power control information back to the base station naturally lends itself to the implementation of the stepped form of power control, whereas an analogue technique would be synonymous with the use of continuously variable base station output power.

Obviously, an analogue power control system in which the base station output power level is continuously variable is analogous to a digital scheme in which the steps in the output power are of an infinitesimally small size. The use of digital techniques and discrete power levels restricts the degree of match possible between base station transmitter power and mobile received signal quality. Depending on the operational characteristics of such a system the match could be up to a whole power control step in error, which if we assumed a base station power control system identical to that as used for mobile power control in TACS, could mean in excess of twice the output power being transmitted as required. The use of smaller steps could ensure a closer match between the output power and signal quality, but would obviously involve the transmission of more data in order to specify a particular power level. If however, the system operated on a step-up step-down principle as opposed to specifying a particular power level, then the amount of data transference necessary to affect a change in base station power would be an irreducible minimum since only two possible commands would exist. For small changes in output power this type of operation would be ideal, however, for a sudden large change in power level, the time taken for this type of system to react and correct the power level/signal quality imbalance could be longer than that for a system which specified a particular power level.

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CHAPTER EIGHT

TIME AND FREQUENCY ASPECTS OF BASE STATION POWER CONTROL

8.1 INTRODUCTION

The general objective of a base station power control scheme is to control the output power of a base station transmitter such that only the minimum necessary power is transmitted to provide the required signal quality at the mobile receiver. Since the quality of the signal received in mobile communications is largely dependent on the propagation characteristics of the radio channel, then it is clear that any base station power control system must aim to overcome some, if not all, of the possible features encountered under such conditions. Numerous studies of LMR propagation have shown that a radio channel can be characterised by the three distinct aspects of fast fading, shadowing, and path loss. Thus the ideal power control system can be envisaged as one in which the variability in received signal quality caused by all of these features is removed.

The relatively slow rate at which path loss and shadowing effects can cause variations in mobile received signal quality should cause no significant problems in the implementation of a base station power control system aimed at removing these transmission characteristics. However, the speed at which fast fading can occur, especially in the higher frequency bands such as those allocated to cellular systems, makes not only the desirability of performing such power control questionable when considering the spectral consequences, but also raises doubts as to the ability to implement a sufficiently swift control scheme.

This chapter investigates the time and spectral properties, and hence feasibility, of a base station power control scheme aimed at removing fast fading variations in mobile received signal quality. The rate at which the received signal level can change under fast fading conditions is assessed and hence the speed at which a base station must be capable of changing its output power is identified. The resultant broadening of the RF output spectrum of a base station transmitter caused by such a power control system is also estimated and presented. The major sources of time delay present in a power control system are identified and their effect on the operation, and hence feasibility, of this type of power control scheme are discussed.

8.2 SPECTRAL PROPERTIES OF A FAST FADING BASE STATION POWER CONTROL SCHEME

The variations in the output level of a base station transmitter equipped with power control can be regarded as a form of amplitude modulation superimposed on top of the already frequency modulated signal. Hence, the output spectrum from a base station with power control will contain sidebands due not only to frequency modulation, but also to the 'AM' power control waveform, thus resulting in a widening of the overall spectrum. The degree to which the frequency spectrum is broadened is obviously dependent on the frequency content of the power level variations, which, for a power control system aimed at removing fast fading variations, could be significant.

The fast fading phenomenon encountered in mobile radio propagation may be considered as the result of interference between a number of incoming waves that have been scattered from obstacles in close proximity to the mobile. Analysis of the resulting interference situation has been carried out by many authors [(1),(2)], and mathematical models have ensued [(3),(4),(5)] which enable the prediction of various statistical properties of the signal pattern. Of these numerous models, that proposed by Gans [(5)] is highly regarded and widely quoted, probably because of the physically reasonable assumptions on which it is based. In this model, the signal at any point in space is considered to be the vectorial sum of a number of horizontally travelling plane waves with random amplitudes and angles of arrival. The phases of the waves are uniformly distributed from 0 to 2π, and the amplitudes and phases are assumed to be statistically independent. Depending on the phase relationship between the incoming waves, they can combine either constructively or destructively, producing deep fades which, on close inspection, resemble a rectified sine wave [6], with minima and maxima spaced on the order of a quarter carrier wavelength.

By way of the very nature of fast fading, exact analysis of such variations in mobile received signal level is not feasible. However, using Gans' model of fast fading, together with certain assumptions, it is possible to make an instructive examination of the shape of fades, from which an estimate of the rate of change of mobile received signal level can be obtained, and hence an indication of the corresponding speed with which base station transmitter power would have to change if it were to remove such fading effects. If we consider the most simplistic case of multipath interference, then the situation can be depicted as shown in Figure 8.1. The signal received at the mobile consists of only two incoming waves, both of which have undergone similar path loss and shadowing effects, but one of which has come direct from the base station and one via reflection from an obstacle in the near vicinity of the mobile. For an unmodulated carrier signal transmitted from the base station, the direct received signal, E_D, can be expressed as

$$E_D = \cos(\omega_c t + \theta_D) \qquad (8.1)$$

where ω_c is the carrier frequency of the transmitted signal and

$$\theta_D = \omega_D t + \phi_D \qquad (8.2)$$

where ϕ_D is a random phase angle and ω_D is the Doppler shift introduced into the wave by the motion of the mobile and expressible as

$$\omega_D = \beta v \cos\alpha_D \qquad (8.3)$$

where α_D is the angle of arrival of the wave at the mobile relative to the direction of motion of the vehicle, v is the velocity of the vehicle, and $\beta = 2\pi/\lambda$, λ being the wavelength of the transmitted carrier signal.

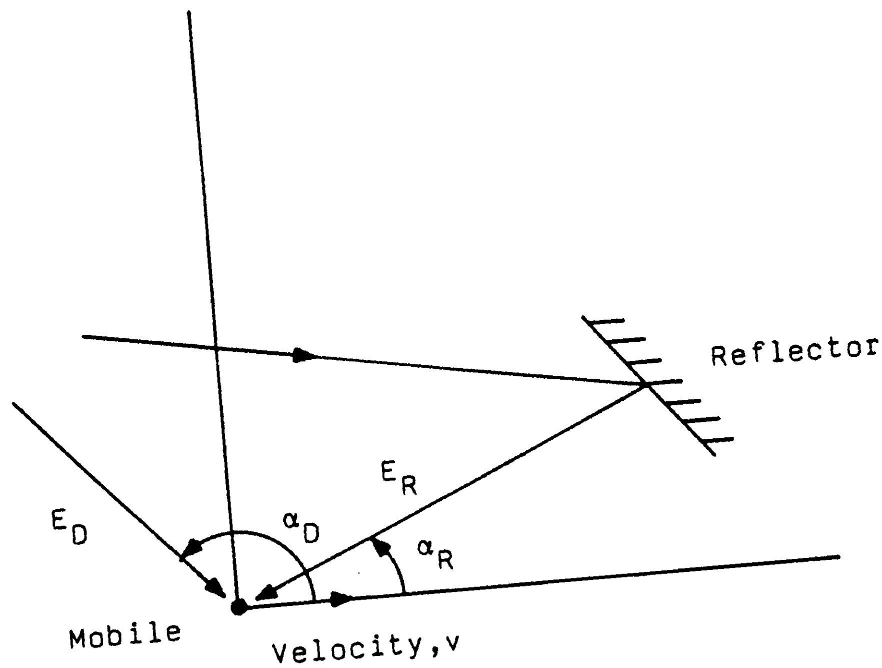

Figure 8.1. Simple Model of Multipath Interference.

The reflected wave, E_R, can be written in a similar form as

$$E_R = b\cos(\omega_c t + \theta_R) \tag{8.4}$$

where b is the attenuation co-efficient of the reflected signal relative to that of the direct signal, and the other parameters are the corresponding equivalents of the direct signal definitions.

If we assume that the direct wave and the reflected wave arrive at the mobile in line with the direction of travel of the vehicle, but from opposite directions, then the resultant mobile received signal will possess the deepest possible fade in the shortest possible time and hence provide a worst case scenario for the power control system. Under these conditions, the signal received by the mobile, E_T, is given by

$$E_T = \cos(\omega_c t - \beta vt + \phi_D) + b\cos(\omega_c t + \beta vt + \phi_R) \tag{8.5}$$

Since it is only the magnitude of the received signal that is of particular interest, then it is merely the modulus of the expression for the mobile received signal that warrants further consideration. This is simply given by

$$|E_T| = \sqrt{1 + b^2 + 2b\cos(2\beta vt + \phi)} \qquad (8.6)$$

where ϕ is the phase difference between the two waves.

This ca$|E_T| = \sqrt{1 + b^2 + 2b\cos(\gamma(t))}$

$$|E_T| = \sqrt{1 + b^2 + 2b\cos(\gamma(t))} \qquad (8.7)$$

where $\gamma(t) = 2\beta vt + \phi$.

The maxima and minima in the received signal level will obviously occur when the trigonometric function, $\cos\gamma(t)$ has the values of +1 and -1 respectively. These two conditions correspond to a maximum value of received signal level of $(1 + b)$ and a minimum value of $(1 - b)$. If this maximum value is used as a reference level, then the depth of fade, FD, experienced by the mobile, in dB, is expressible as

$$FD = 20\log\left(\frac{1 - b}{1 + b}\right) \qquad (8.8)$$

and the received signal level in dB, E, is given by

$$E = 20\log\left(\frac{|E_T|}{1 + b}\right) \qquad (8.9)$$

From equation (8.8) the value of b for various fade depths can be calculated, which when used in conjunction with equation (8.9) permits the shape of fades to be investigated. Figure 8.2 shows the shape of fades ranging from depths of 5dB to 40dB.

Substituting equation (8.6) into equation (8.9) gives the relationship for the received mobile signal level in dB as

$$E = 20\log\left(\frac{\sqrt{1 + b^2 + 2b\cos(2\beta vt + \phi)}}{(1 + b)}\right) \quad (8.10)$$

Since β is fixed for a given carrier frequency, if we assume that the vehicle is travelling at a constant velocity, then this expression can be easily differentiated with respect to time to obtain the rate of change of received signal level (dB per second), and hence the required rate of change of base station transmitter power. If we take a carrier frequency of 900MHz, then $\beta = 6\pi$ and equation (8.10) becomes

$$E = 20\log\left(\frac{\sqrt{1 + b^2 + 2b\cos(12\pi vt + \phi)}}{(1 + b)}\right) \quad (8.11)$$

Differentiating this equation gives

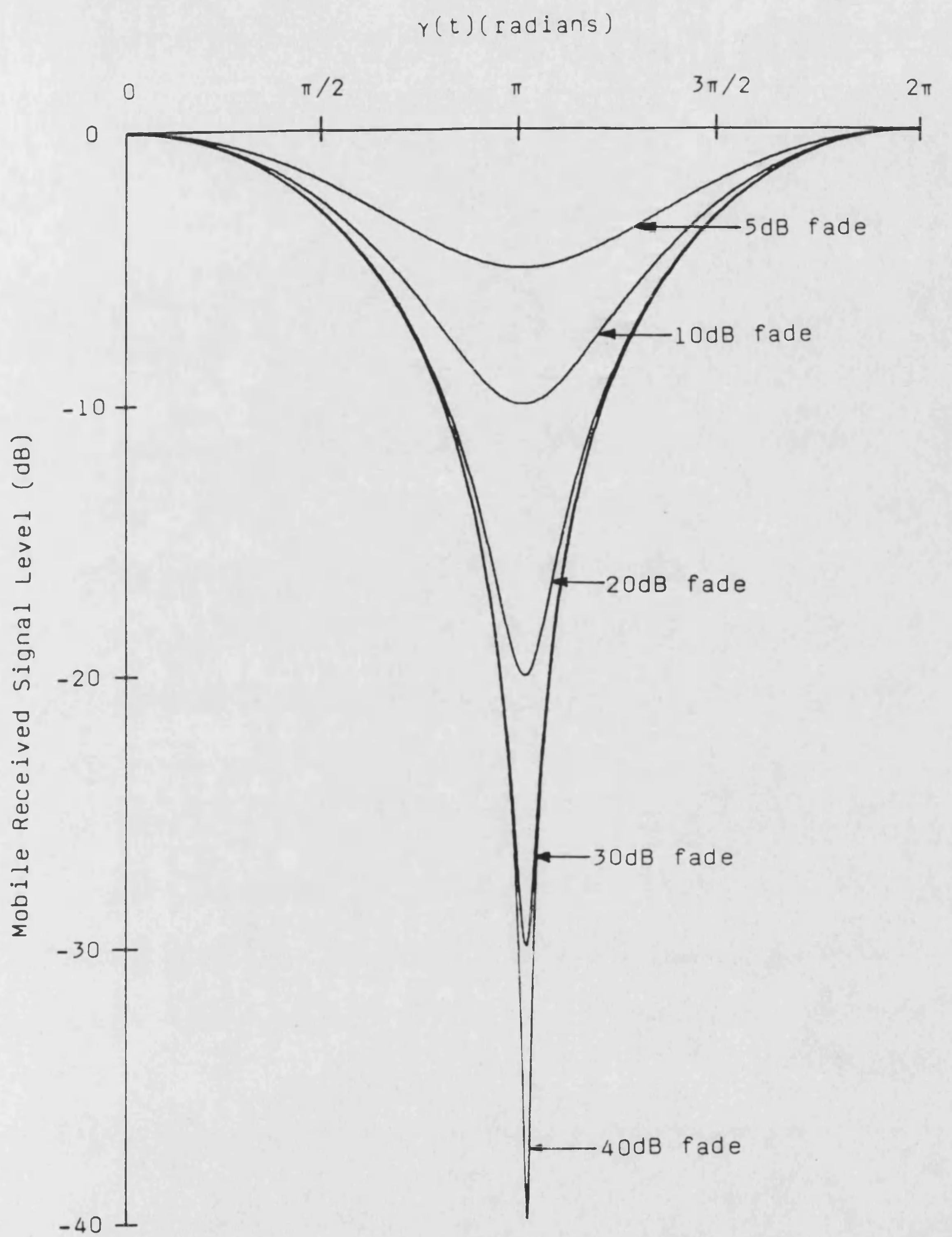

Figure 8.2. The Shape of Fades.

$$\frac{dE}{dt} = - \frac{240\pi vb\sin(12\pi vt + \phi)}{\ln 10(1 + b^2 + 2b\cos(12\pi vt + \phi))} \qquad (8.12)$$

Figures 8.3 to 8.6 show the rates of change of received signal level for various vehicle speeds for fade depths of 10dB, 20dB, 30dB, and 40dB respectively. It is apparent from these graphs that a base station power control system aimed at removing such variations in received signal quality would be required to be able to change the output power of the base station transmitter at a fairly substantial rate. This, in turn, would result in an overall widening of the RF output spectrum of the transmitter. The extent of broadening on the output spectrum can be examined by using the fact that at constant vehicle speed, the fast fading pattern experienced at the mobile has a regular nature, and so the expression for the variation in received signal level, and hence the corresponding expression for the variation in base station output power, may be considered as a periodic function. This does however entail making the assumption that all fades experienced by the mobile are of the same depth. This obviously not being the case in practice, does not enable a true representation of the spectrum spreading to be analysed. However, if we assume that all fades are of the maximum depth generally encountered in a practical system, then a worst case scenario can be

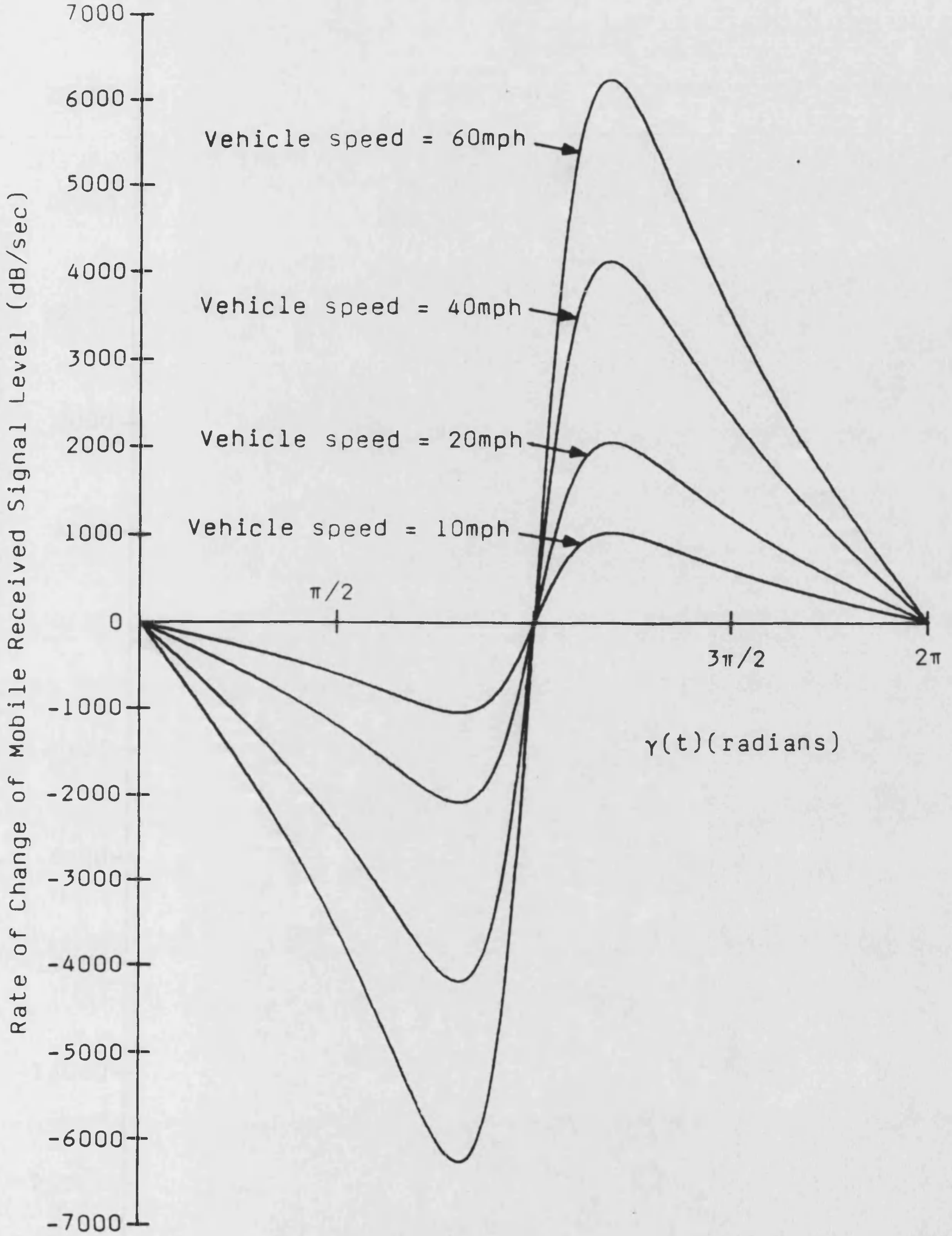

Figure 8.3. Rate of Change of Mobile Received Signal Level During a 10dB Fade.

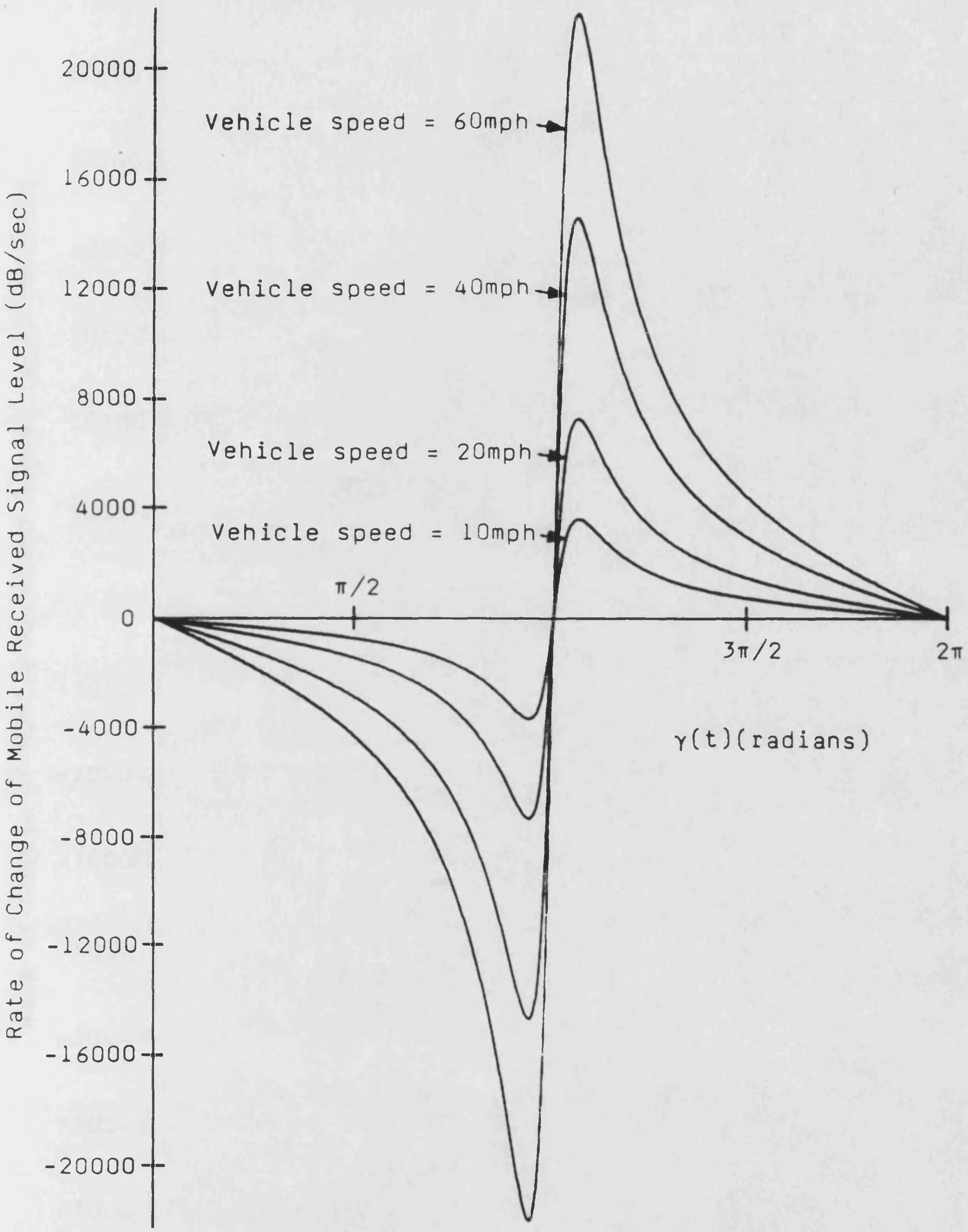

Figure 8.4. Rate of Change of Mobile Received Signal Level During a 20dB Fade.

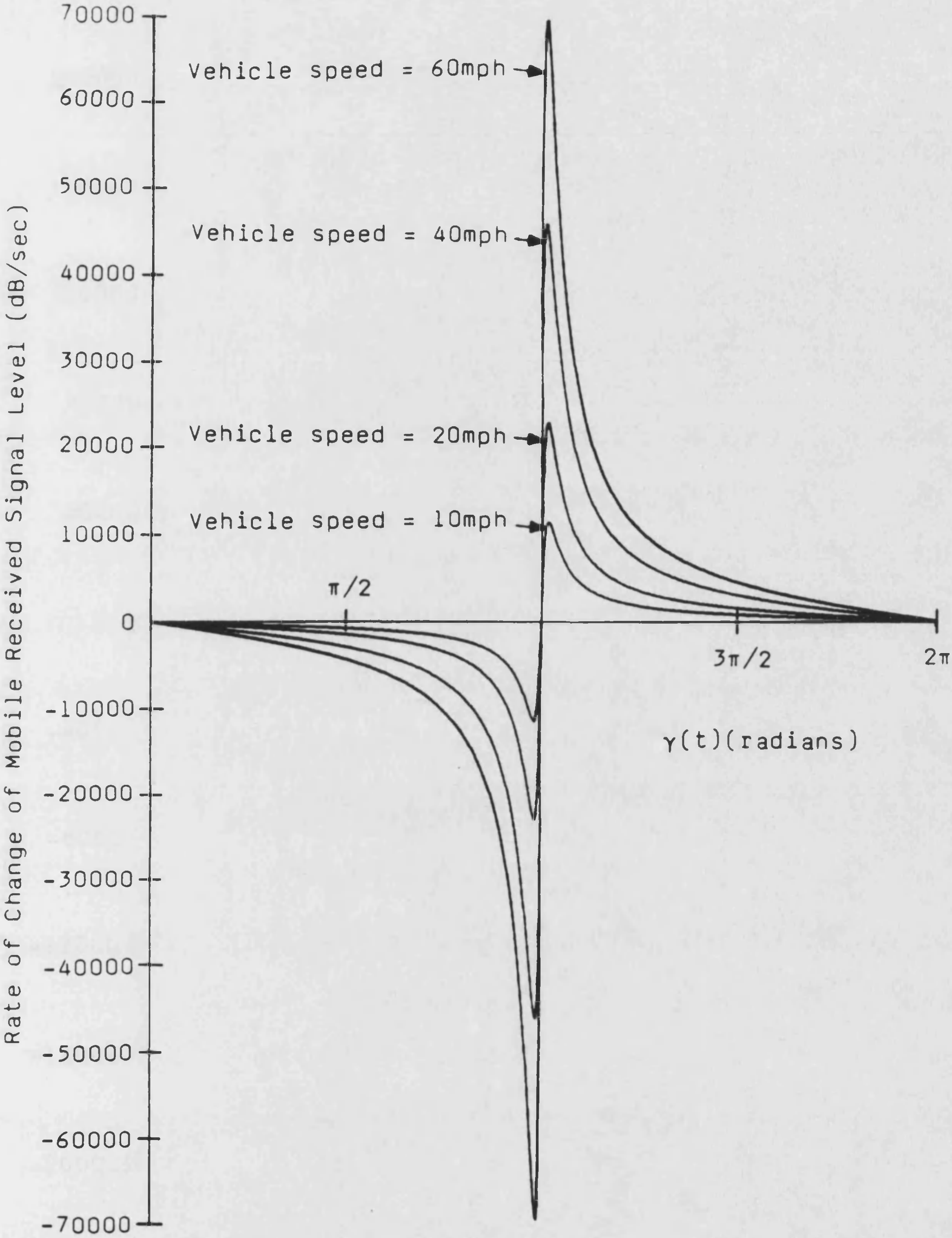

Figure 8.5. Rate of Change of Mobile Received Signal Level During a 30dB Fade.

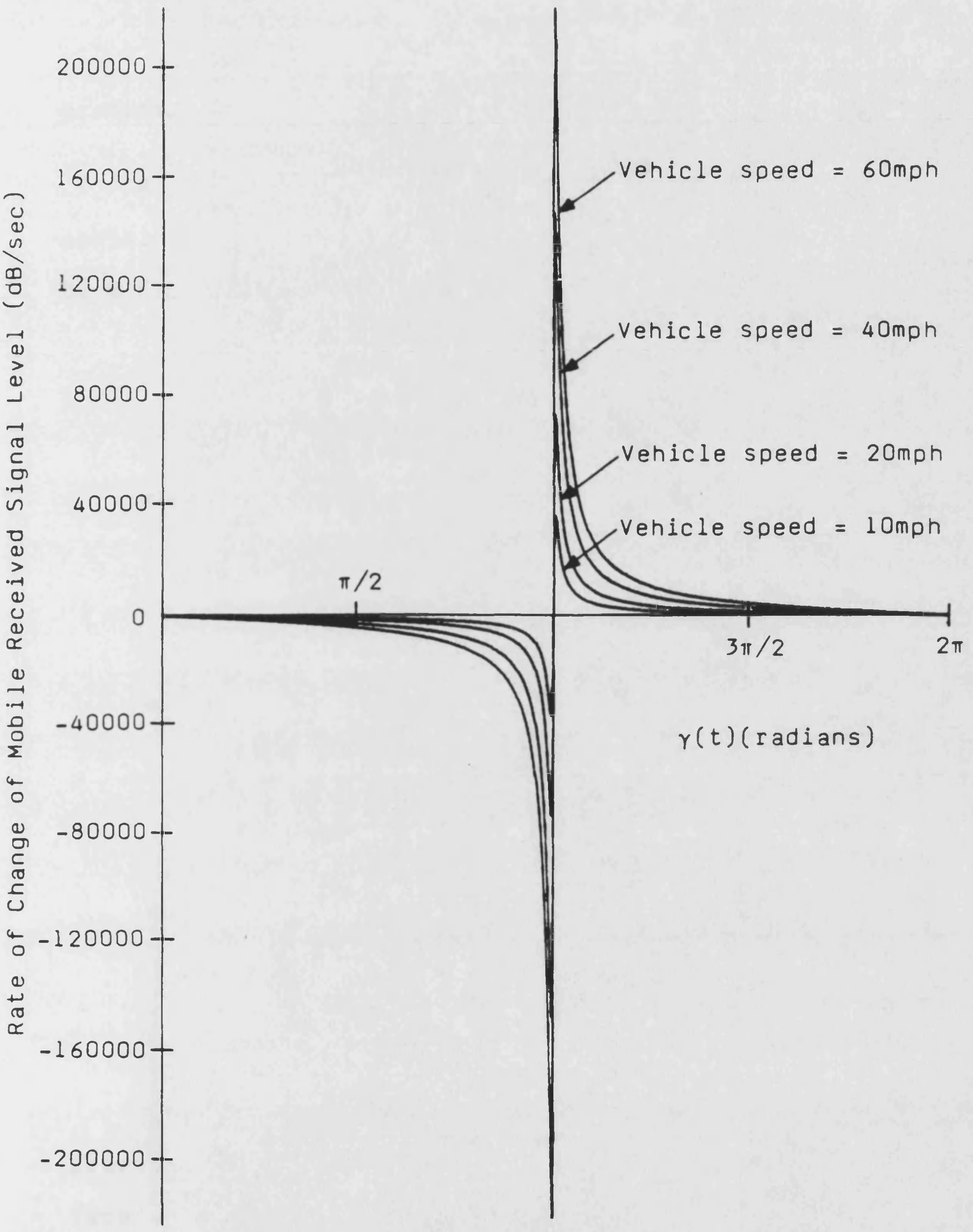

Figure 8.6. Rate of Change of Mobile Received Signal Level During a 40dB Fade.

produced and examined.

A periodic function, $f(t)$, of period T, and fundamental frequency ω, where $\omega T = 2\pi$, can be represented by a Fourier series of the form

$$f(t) = A_0 + \sum_{n=1}^{\infty} (A_n \cos n\omega t + B_n \sin n\omega t) \qquad (8.13)$$

where A_0 is the average value of $f(t)$ given by

$$A_0 = \frac{1}{T}\int_{-T/2}^{T/2} f(t)\, dt \qquad (8.14)$$

while the co-efficients A_n and B_n are given by

$$A_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\cos n\omega t\, dt \qquad (8.15)$$

and

$$B_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\sin n\omega t\, dt \qquad (8.16)$$

If we assume that the required signal strength to provide the desired reception quality corresponds to a received signal level of $(1 + b)$, then, from a spectrum broadening point of view, the required base station transmitter output, $P(t)$, can be regarded as an AM waveform expressible by the equation

$$P(t) = (2 + 2b - (1 + b^2 + 2b\cos(12\pi vt + \phi)))\cos\omega_c t \qquad (8.17)$$

Using the Fourier series representation, $P(t)$ can also be written as

$$P(t) = (A_0 + \sum_{n=1}^{\infty} A_n \cos n\omega t + B_n \sin n\omega t)\cos\omega_c t \qquad (8.18)$$

Since ϕ only affects the time at which the maxima and minima in the received signal occur, then setting $\phi = 0$ merely references the waveform such that at $t = 0$ the received signal level is at a maximum, and hence $P(t)$ becomes an even function. This simplifies the calculation of the frequency spectrum of $P(t)$, since for an even function $B_n = 0$ for all n. Thus $P(t)$ becomes expressible as

$$P(t) = (A_0 + \sum_{n=1}^{\infty} A_n \cos n\omega t)\cos\omega_c t \qquad (8.19)$$

Combining equations (8.17) and (8.19) we obtain the equation

$$(A_0 + \sum_{n=1}^{\infty} A_n \cos n\omega t) = (2 + 2b - (1 + b^2 + 2b\cos 12\pi vt)) \tag{8.20}$$

from which the output spectrum of the base station transmitter can be calculated using numerical techniques [7].

Figures 8.7 to 8.10 show the resultant spectrum of the base station transmitter for a fade depth of 40dB at vehicle speeds ranging up to 80mph. It can be seen from these spectra that the broadening of the base station output brought about by such a power control system is perhaps less than would be imagined. As would be expected, doubling the speed of the mobile causes a doubling in the width of the spectrum, but even at 80mph and a frequency of 900MHz, the spectrum is such that, for sideband amplitudes greater than -100dB relative to that at the carrier frequency, it is still only approximately $\pm$ 15kHz wide. It is perhaps worth remembering at this stage that these spectra are for an unmodulated carrier. Obviously, for an FM signal, every sideband of the FM spectrum would be affected in a similar manner causing possible further spreading. Figures 8.11 and 8.12 show the computed output spectrum for the base station transmitter with a modulating fre-

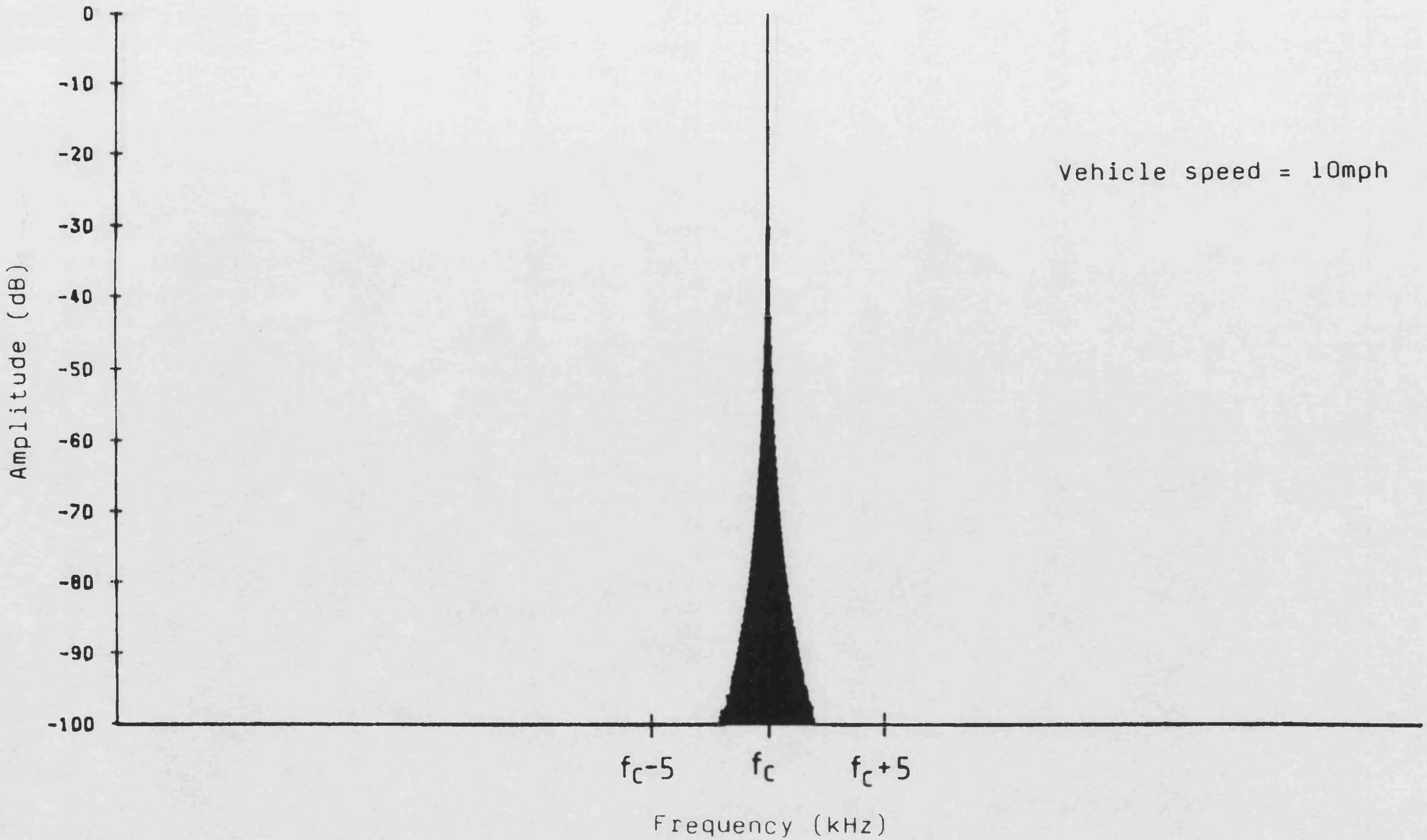

Figure 8.7. Output Spectrum of a Base Station Transmitter Correcting for a 40dB Fade

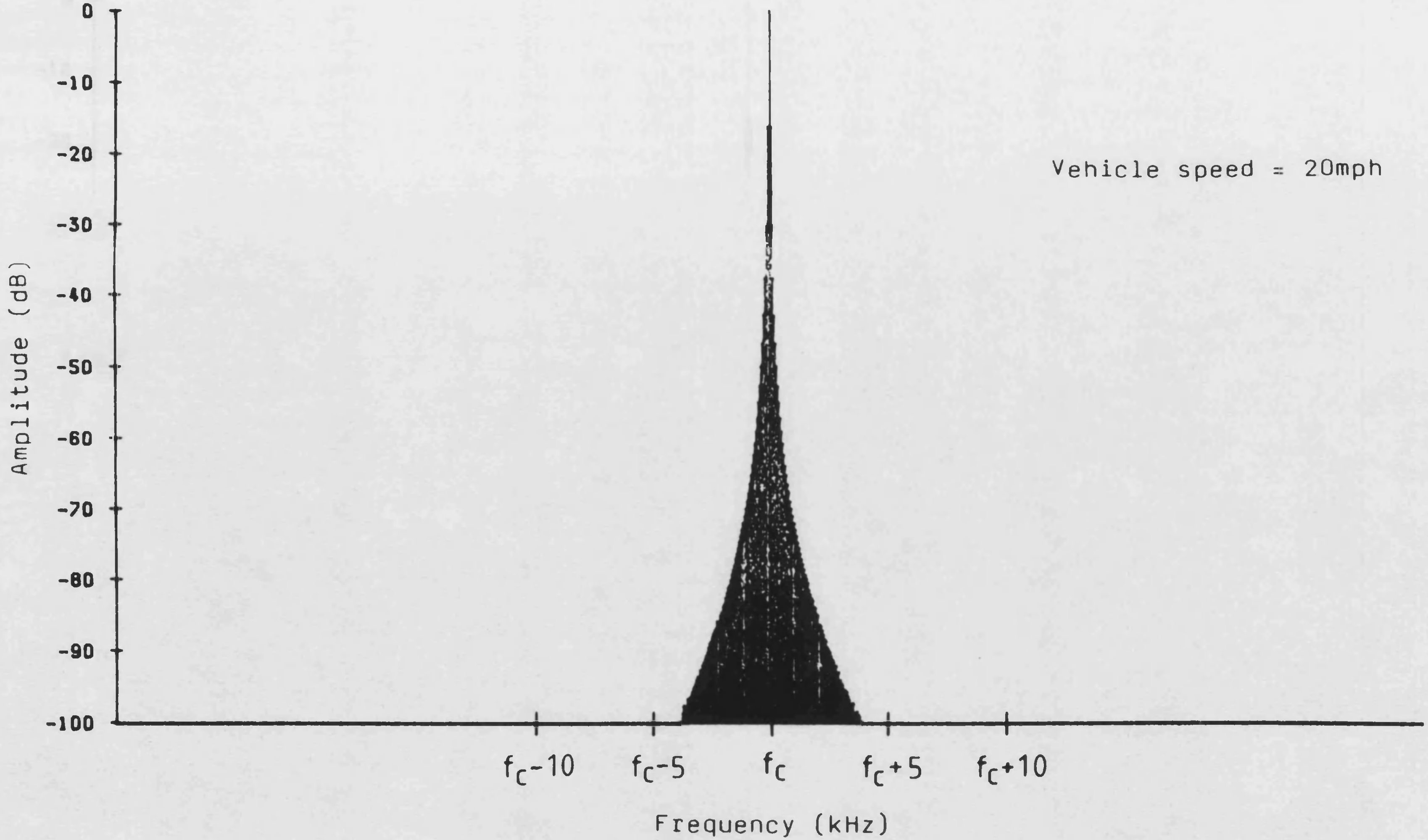

Figure 8.8. Output Spectrum of a Base Station Transmitter Correcting for a 40dB Fade

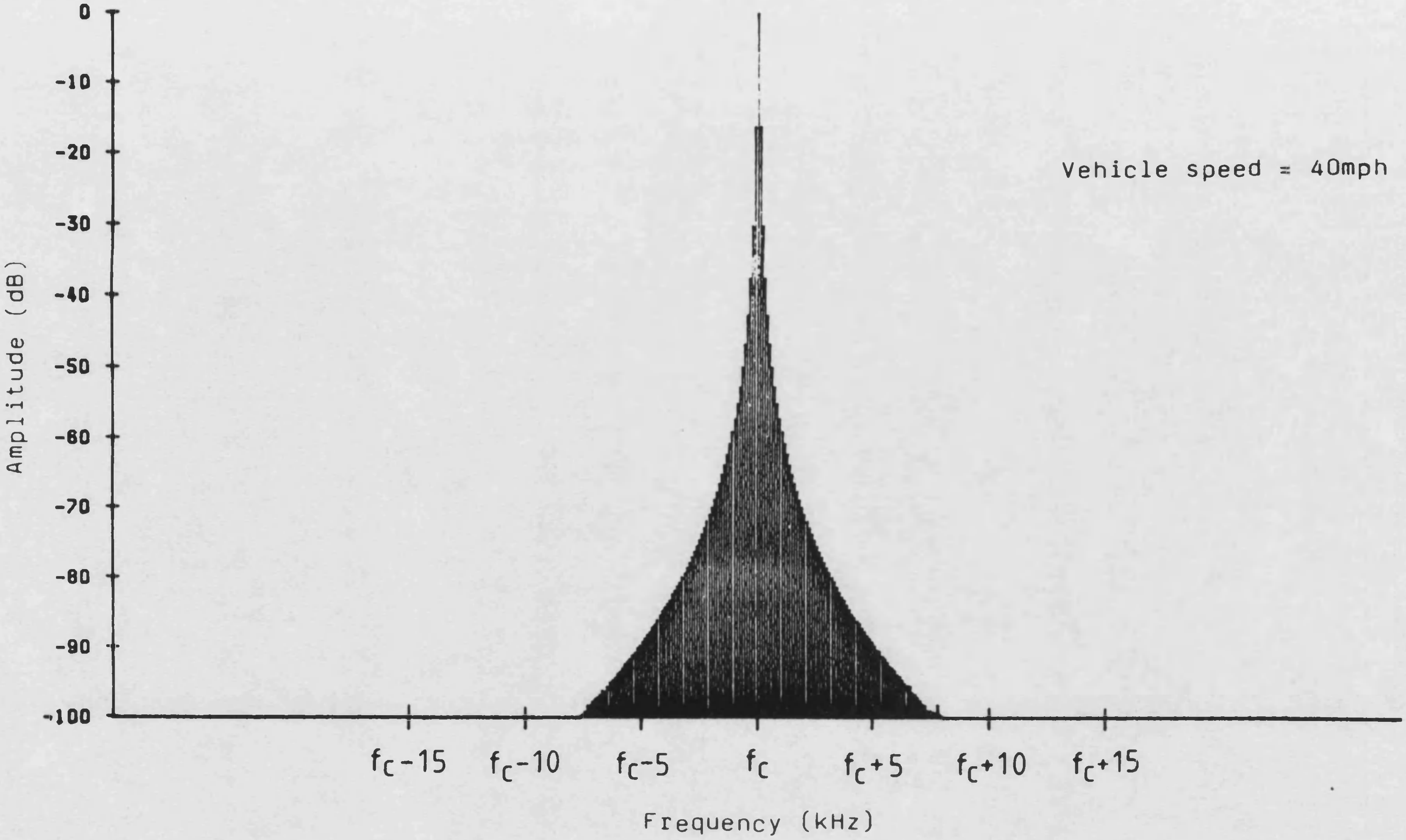

Figure 8.9. Output Spectrum of a Base Station Transmitter Correcting for a 40dB Fade

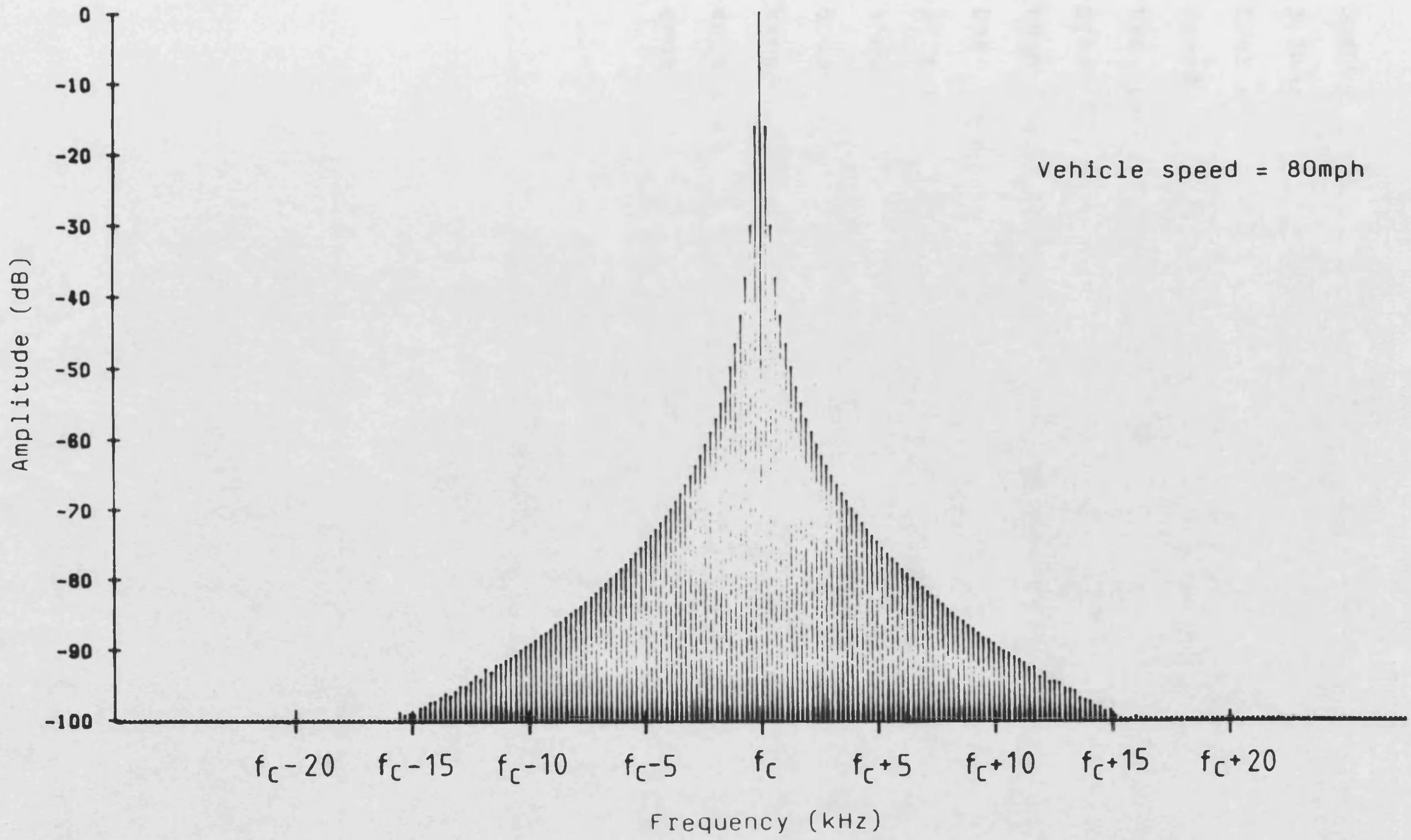

Figure 8.10. Output Spectrum of a Base Station Transmitter Correcting for a 40dB Fade

quency of 1kHz and a peak frequency deviation of 3.3kHz, for the case of no power control and power control whilst correcting for a 40dB fade at a mobile speed of 80mph respectively. A comparison between the two spectra show that although the number of sidebands present in the power control case is vastly greater than that without such control, the overall width of the two spectra are remarkably similar. Thus, the use of a fast fading base station power control system should not result in any significant broadening in the output spectrum of the base station transmitter, and hence should not give rise to any higher levels of adjacent channel interference than at present experienced.

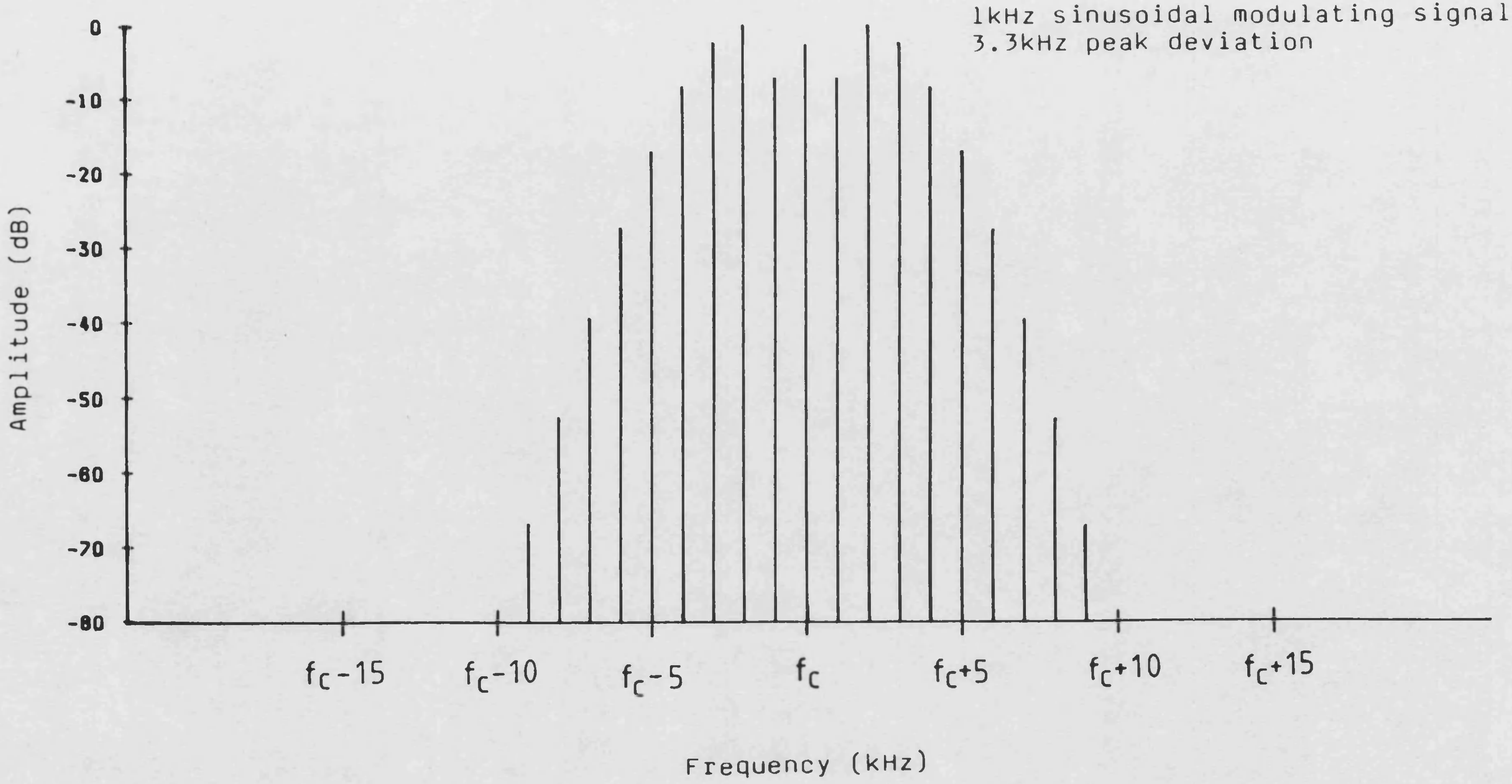

Figure 8.11. Output Spectrum of a Base Station Transmitter with Frequency Modulation.

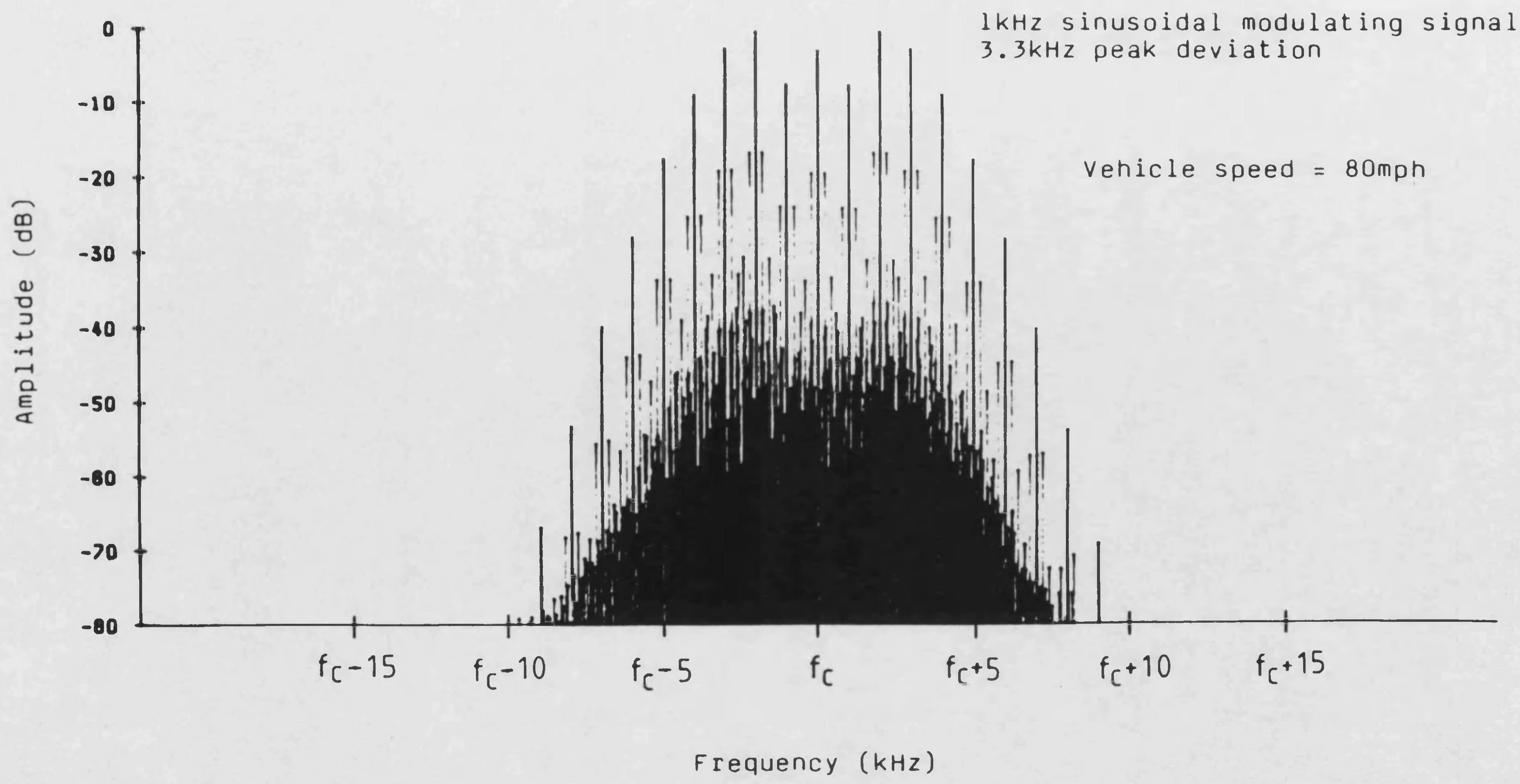

Figure 8.12. Output Spectrum of a Base Station Transmitter with Frequency Modulation Correcting for a 40dB Fade.

8.3 THE TIME ASPECTS OF A FAST FADING POWER CONTROL SCHEME

The ability of a base station power control scheme to perform fast fading corrections in mobile received signal quality is obviously very much dependent on implementing a sufficiently rapid power control system. The overall response time of a power control scheme will naturally depend largely on the manner in which the control system operates, but will also be affected, to a varying extent, by the various time delays that inevitably exist within mobile radio equipment.

The implementation of a power control scheme based on a reciprocal propagation assumption can be seen to provide the fastest possible control system since this would ensure not only the minimum amount of radio equipment incorporated into the control system, but also that the processing requirements to accomplish the power control function were minimal. However, the separate receive and transmit antenna configurations together with the diversity reception techniques that are now being increasingly adopted at base station sites effectively makes fast fading a non-reciprocal propagation feature and hence such a power control system implementation cannot readily be used to combat such variations in mobile received signal quality.

The use of a non-reciprocal base station power control implementation technique naturally dictates a loop control system incorporating both mobile and base station transmitters and receivers and the intervening propagation path. The removal of fast fading variations will undoubtedly require a continuous assessment of received signal quality at the mobile together with the corresponding continuous transmission of power control information back to the base station. This need for continuous assessment and transmission not only restricts such a power control scheme to duplex radio systems, but also limits the manner in which this type of power control system could be implemented to the techniques discussed in the previous chapter that can accommodate such requirements.

The use of signal level as oppose to phase jitter as a measure of received signal quality would ensure that the delay in the power control system due to mobile processing was minimal since such a measurement could certainly be made quicker and at an earlier point within the mobile receiver. The relatively slow rate at which continuous data would have to be transmitted along with the normal audio in order to remain within bandwidth restrictions could result in fade rates approaching data rates for the higher frequency bands, and hence would almost certainly preclude the use of a digital format for conveying the power control information between mobile and base station. The use of an analogue technique would not only be potentially quicker in relaying the power control information but would also offer the ability to control the base station output power in a non discrete manner, thus avoiding continuous abrupt changes in output power and the associated spectral effects.

The major delays in a power control system due to the radio equipment would occur in the filters of mobile and base station transceivers. The crystal and ceramic filters that are invariably used in the IF stages of mobile and base station receivers in order to provide selectivity are two main sources of such delay. Group delays of around 150-200μs are common for the crystal filters presently used in receivers, whilst group delays approaching 100μs are generally found to exist in the ceramic filters. Since the loop control system includes both base station and mobile receivers, then the total delay introduced into the control system by these filters would be in the region of 0.5ms.

In cellular systems, the use of wideband data transmissions between mobile and base station requires the use of crystal and ceramic filters that are wider than those normally used in LMR equipment. This, together with the fact that the crystal filter is of a lower order than those normally used, all results in the time delay associated with these components being less than those of their counterparts in conventional LMR systems. Thus the delay introduced into a power control system operating in a cellular scheme by such components would be understandably less. The use of wider and lower order crystal and ceramic filters by other LMR systems would also reduce the time delay introduced by such components into their power control schemes, but the accompanying reduction in selectivity of such action would probably be unacceptable.

The response time required by a power control system in order to successfully remove fast fading variations in mobile received signal quality is clearly dependent on the frequency band in which the radio scheme is operating. Obviously, for LMR systems operating in the lower frequency bands the rate at which fast fading can occur is much slower than that for systems operating in the higher bands, and hence the corresponding power control system can afford to be slower. Fundamentally more important to the required speed for such a power control scheme is the motion of the mobile unit since it is this that directly gives rise to such fast fading effects. If the mobile is stationary or near stationary then the fluctuation rates experienced are orders of magnitude less than those that can be encountered at normal vehicle speeds.

Taking all factors into consideration, it seems very unlikely that a fast fading power control scheme could ever be implemented with a sufficiently rapid response as to be used in UHF LMR schemes. If base station power control were to be used to remove such variations in mobile received signal level, it would have to be restricted to mobile systems operating at lower frequencies where fading rates should prove to be more favourable towards the implementation of this type of control system.

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CHAPTER NINE

PRACTICAL PERFORMANCE OF A MOBILE RADIO SYSTEM WITH BASE STATION POWER CONTROL

9.1 INTRODUCTION

In chapter seven some of the practical aspects associated with base station power control in mobile radio systems were discussed, and possible methods of implementing such a control scheme were identified and examined. Of the numerous ways in which base station power control could be performed, it can be appreciated that each method would possess its own characteristics as regards practical implementation and overall performance.

The use of a base station power control scheme to remove the fast fading variations encountered in mobile communications was discussed in chapter eight. It was concluded that the use of fast fading power control would be extremely unlikely, at least for LMR systems operating in the UHF bands, when considering the rate at which the control system would have to operate, bearing in mind the time delays that would exist in such a control scheme. Thus, it is believed, that the optimum base station power control scheme for these systems is one in which the dependence of mobile received signal quality on shadowing and path loss factors is completely removed. Obviously, to enable the close match necessary between mobile received signal quality and base station output power requires the system to be such that the signal quality is monitored, and the power changed, in a continuous rather than discrete manner.

This chapter details the design and development of a base station power control system aimed at performing this optimum power control function. The system is designed so that only a minimum of additional hardware is required, and is such that it can be retrospectively fitted to equipment that is already in service. The base station output power is continuously variable over a pre-defined range under control from the mobile using tone signalling techniques. Using received signal level as an indication of signal quality, the results obtained from practical field measurements show that the signal quality received by mobiles can be made completely independent of mobile-base station separation and that the variability caused by shadowing can be significantly reduced. Furthermore, if required, such results could be adapted to examine and assess the performance of discrete base station power control schemes for various system parameters.

9.2 PRINCIPLE OF OPERATION AND GENERAL SYSTEM CONSIDERATIONS

Of the many and varied ways in which a base station power control system could be implemented, it is believed a most effective and readily achievable algorithm for performing such a function is as shown in Figure 9.1. The signal transmitted from the base station is received at the mobile where the quality of the signal is continuously measured and assessed by comparing with a pre-defined level corresponding to the required transmission quality. Any difference between the two levels is immediately converted into a suitable form and the information relayed back to the base station. At the base station, this signal is received and processed into the desired form to increase or decrease the output power of the transmitter, whichever is applicable, to maintain the required signal quality at the mobile. It is clear that the operation of such a control scheme requires simultaneous transmission and reception by both mobile and base station, and hence is only applicable for LMR systems which operate in duplex mode.

Having defined the algorithm that is to be used for the power control system, it is now possible to consider the functions that both mobile and base

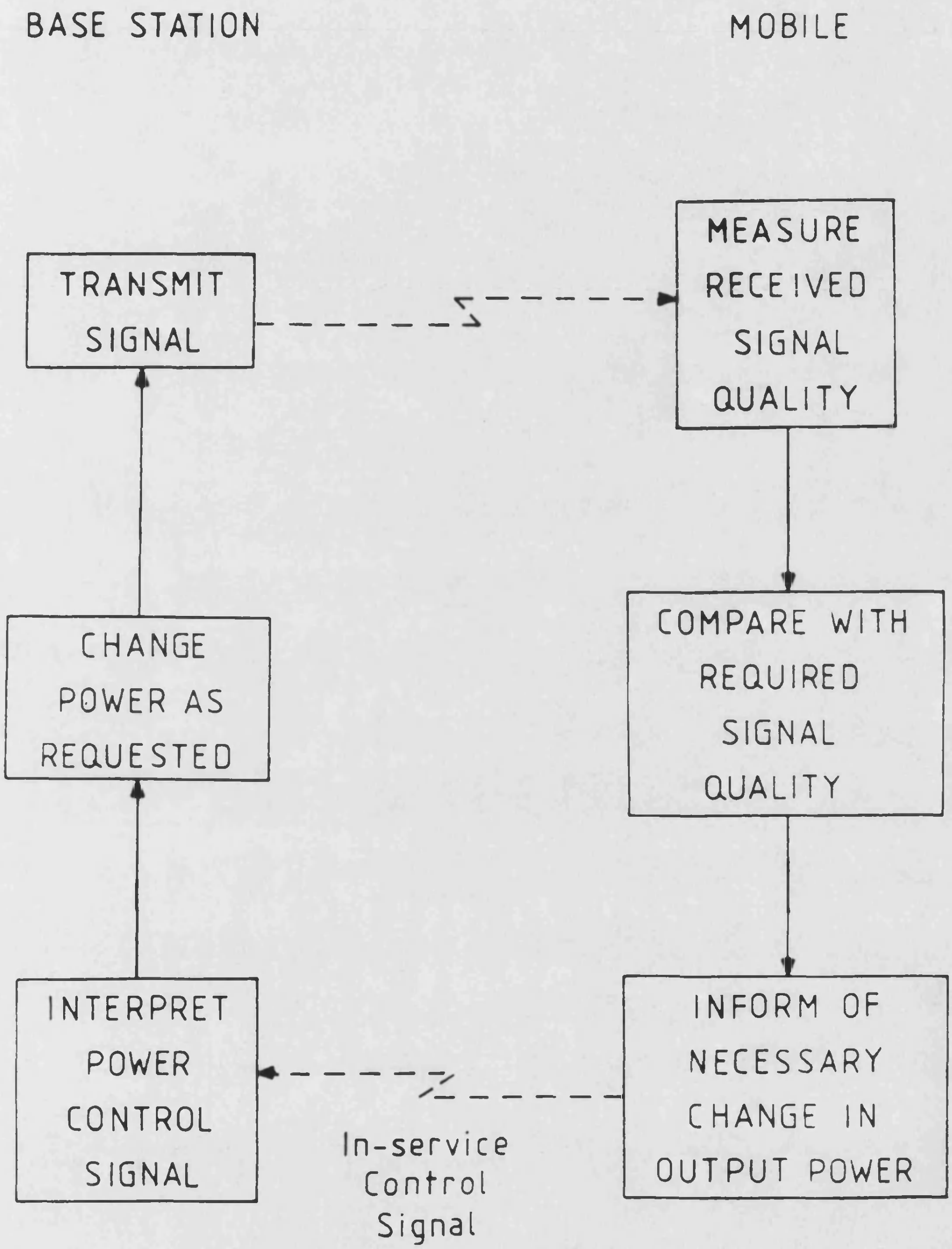


Figure 9.1. Algorithm for Base Station Power Control Operation.

station must perform. Figures 9.2 and 9.3 show schematic diagrams of the mobile and base station transceivers respectively for the proposed power control scheme. The additional hardware required by the mobile in order to perform the power control is a circuit capable of real time assessment of the received signal quality, together with the conversion of this signal quality information into a suitable form which can readily be transmitted back to the base station.

For FM LMR systems, an indication of received signal quality can easily be obtained from a measure of the received signal level. Clearly, the use of such an indication means that a measurement must be taken at a point within the mobile receiver where the signal level shows a constant relationship with the level of the incoming signal, and hence must be made prior to any AGC controlled circuits.

Since the proposed power control system is continuous in operation, the form in which the signal quality information is relayed back to the base station must be itself of a continuous nature. The use of digital techniques obviously does not meet this criterion since they are inherently discrete, and hence some form of analogue signal must be used to convey the power control information. It is also essential that the

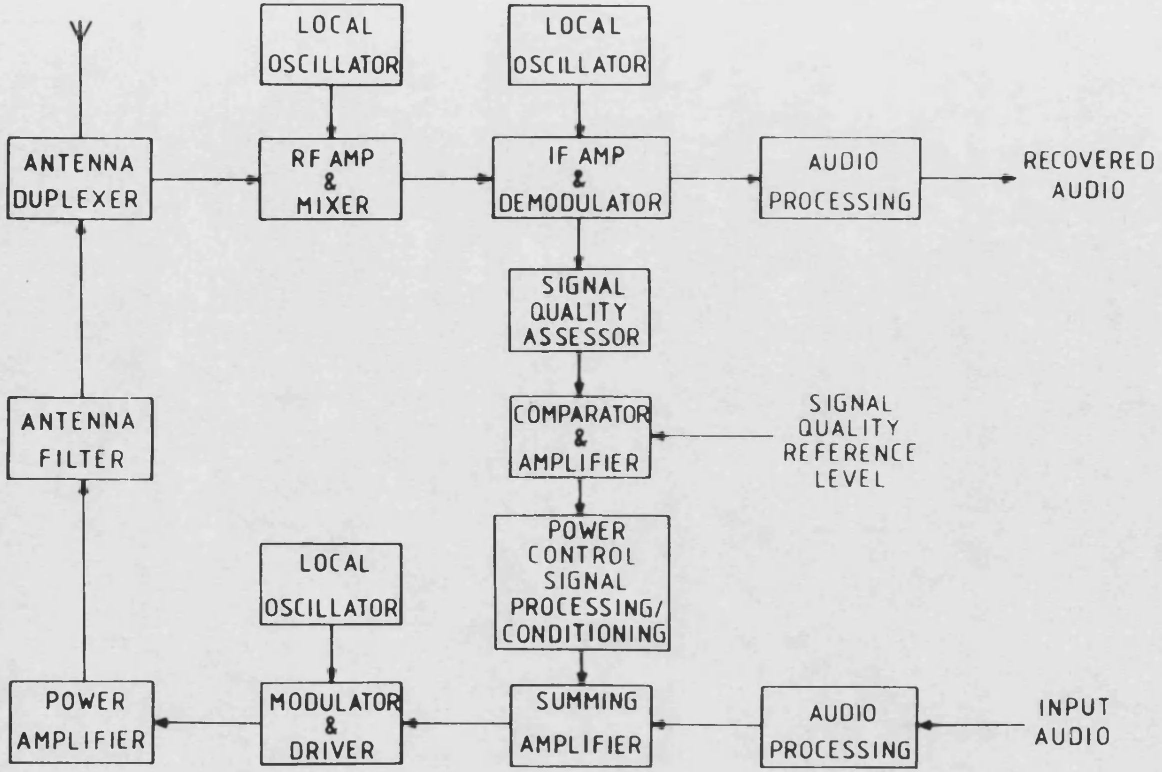


Figure 9.2. Schematic Diagram of Mobile Transceiver for Proposed Power Control System.

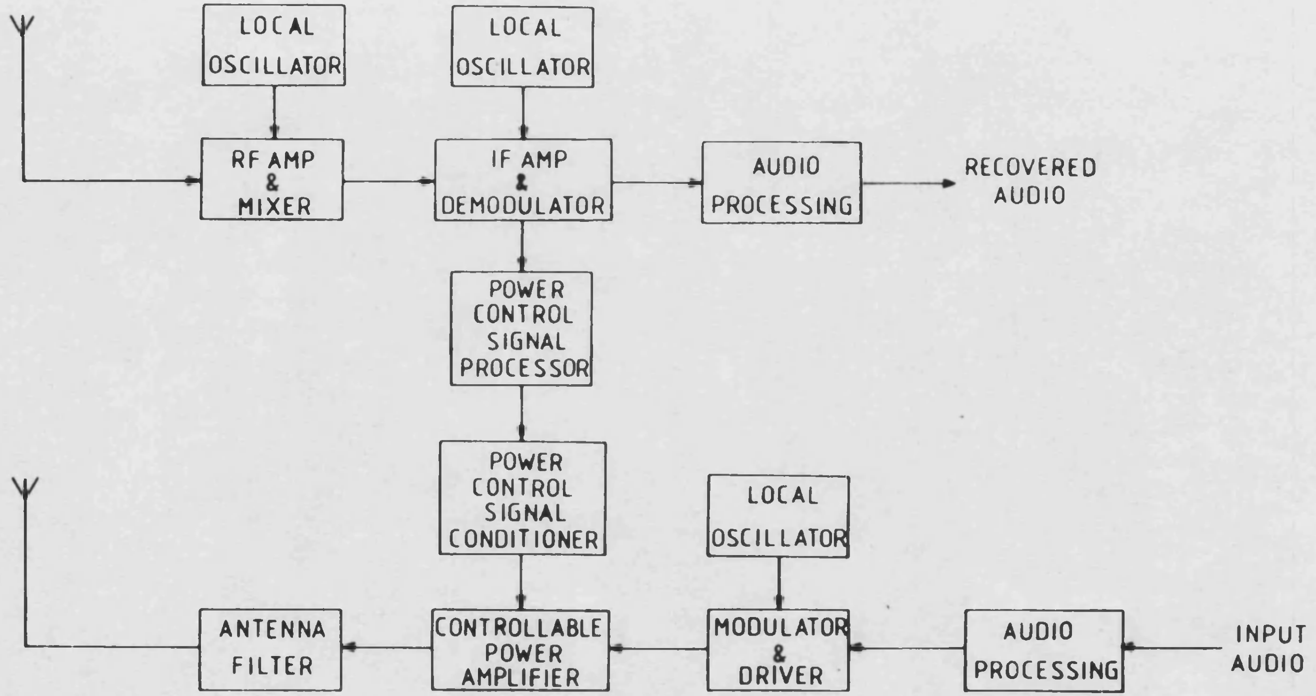


Figure 9.3. Schematic Diagram of Base Station Transceiver for Proposed Power Control System.

information carried by this signal is in no way corrupted by the processing and transmission characteristics it will be subjected to. This requirement obviously leads to the use of a tone located either below, within or above the audio band, the frequency of which is continuously variable over a set bandwidth, and corresponds to a specific level of base station output power. The wider bandwidth available above the audio band is potentially more useful since the tone can be located sufficiently far away from the mobile audio so as to reduce audio filtering requirements, whilst offering a larger range over which the frequency of the tone can be varied, hence giving the system better noise performance. As is common with such tone signalling techniques a low RF frequency deviation must be used for the tone in order to be able to maintain the required deviation level for the mobile transmit audio, whilst still enabling the total system deviation to be kept within the prescribed limits. The use of a low deviation level also aids separation of the tone and the audio at the base station, together with helping to reduce the potential broadening of the RF output spectrum of the mobile.

The additional base station hardware required by the power control scheme is, like that of the mobile, minimal, consisting simply of processing circuits for the power control signal and a circuit to convert the conventional class C power amplifier (PA) into one whose output power can be controlled. In performing the actual power control, it must be borne in mind that for some of the time maximum transmitted power will be required in order to provide an acceptable signal quality at the mobile. Thus, the insertion loss of any conversion circuit must be small in order not to reduce the maximum available transmitted power by any marked degree.

The relatively high powers that can be used by base station transmitters almost certainly rules out performing the power control after the PA stage of the transmitter. Although a certain degree of control over the output power of a PA can be obtained through varying the dc supply to the device, to obtain a reasonable power control range necessitates a large variation in the supply level, which in turn, can lead to instability. Thus control of the output power is limited to a point prior to the PA input. Since most transmitters consist of a discrete drive stage followed by a PA stage, the 100-500mW level generally found at the output of the drive stage gives a convenient low power point at which to control the output power of the transmitter.

Having accepted that it is necessary to effect the power control before the PA stage of the transmitter, an additional factor must be considered, namely the effect on the performance of the PA when operating on lower than normal input signal levels. The magnitude of this factor will depend upon the design of the PA being used, but almost all will show relative increases in spurious and thermal noise. As a consequence, there is likely to exist a lower limit of power, beyond which the increase of transmitted spurious will become unacceptable. The flexibility to set the power control range below the maximum possible is therefore essential.

The processing circuits for the power control signal must be such as to convert the information contained within the frequency of the tone into a suitable form to be used with the power control circuit. Without exception, the circuits capable of performing the power control function will be voltage controlled, and hence the power control information contained within the tone must be converted into a dc voltage level. This can easily be achieved through the use of a simple tone decoding circuit.

9.3 PRACTICAL IMPLEMENTATION OF THE BASE STATION POWER CONTROL ALGORITHM

A practical implementation of the base station power control algorithm was carried out with the aid of two standard FM LMR transceivers. Although originally intended for simplex operation, the two sets were suitably modified to enable back to back duplex working to be achieved in the lower UHF band with base station and mobile transmit frequencies of 456.925MHz and 462.425MHz respectively. The modifications and circuits installed into the two transceivers to enable the power control function to be performed are detailed below.

9.3.1 Mobile Power Control Circuitry

9.3.1.1 Signal Strength Monitoring Circuit

The signal strength monitoring circuit installed in the mobile was based around one of the now readily available low power single conversion FM receiver integrated circuits, the SL6652, which has the added facility of a received signal strength indicator with a dynamic range in excess of 80dB. In order to realise the full dynamic range of the circuit it was necessary that the input to it was taken from a point in the IF strip of the mobile receiver that exhibited a similar dynamic range. Since the received signal strength indicator in the SL6652 is only capable of operating on signals up to 1MHz the obvious point from which to obtain the input was from within the 455kHz IF stages of the mobile. However, saturation within the early stages of the 455kHz IF circuitry of the receiver limited the dynamic range of the signal strength indication to under 40dB and so precluded its use as a possible input to the signal strength circuit without first making extensive modifications to the receiver. Thus the input to the circuit was taken from the 10.7MHz IF stages of the receiver prior to the second mixer where the dynamic range proved sufficient to give a 90dB range of received signal strength indication. The second local oscillator within the mobile receiver was used to perform the necessary down conversion within the SL6652.

Figure 9.4 shows the circuit diagram of the signal strength monitoring circuit whilst Figure 9.5 shows the circuit diagram of the 10.7MHz IF stages of the receiver together with the interconnections to the signal strength circuit. The calibration curve for the signal strength monitor is given in Figure 9.15 on page 248 of the thesis.

To ensure that the signal strength monitoring circuit was in no way affected by the output from the

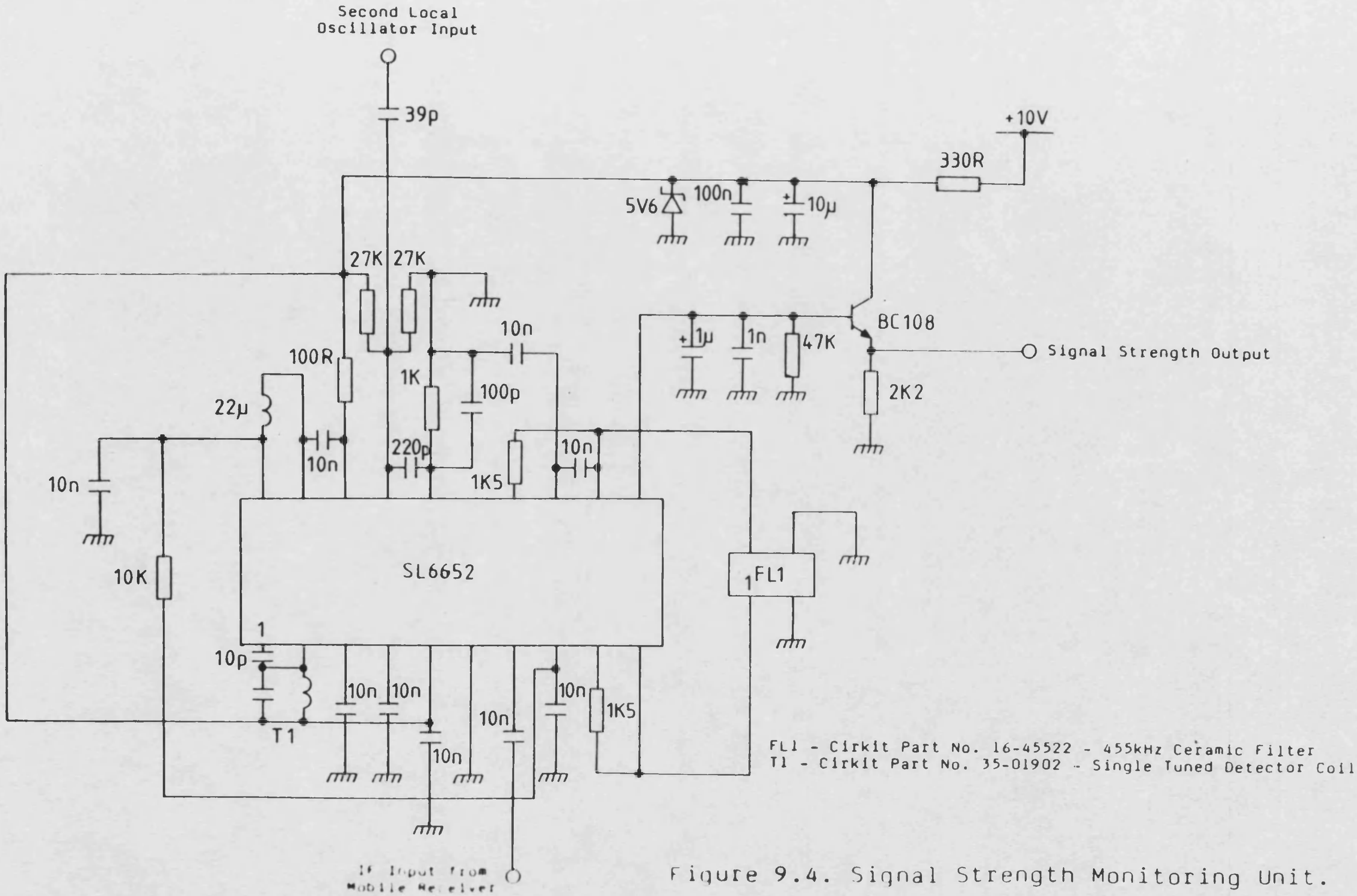


Figure 9.4. Signal Strength Monitoring Unit.

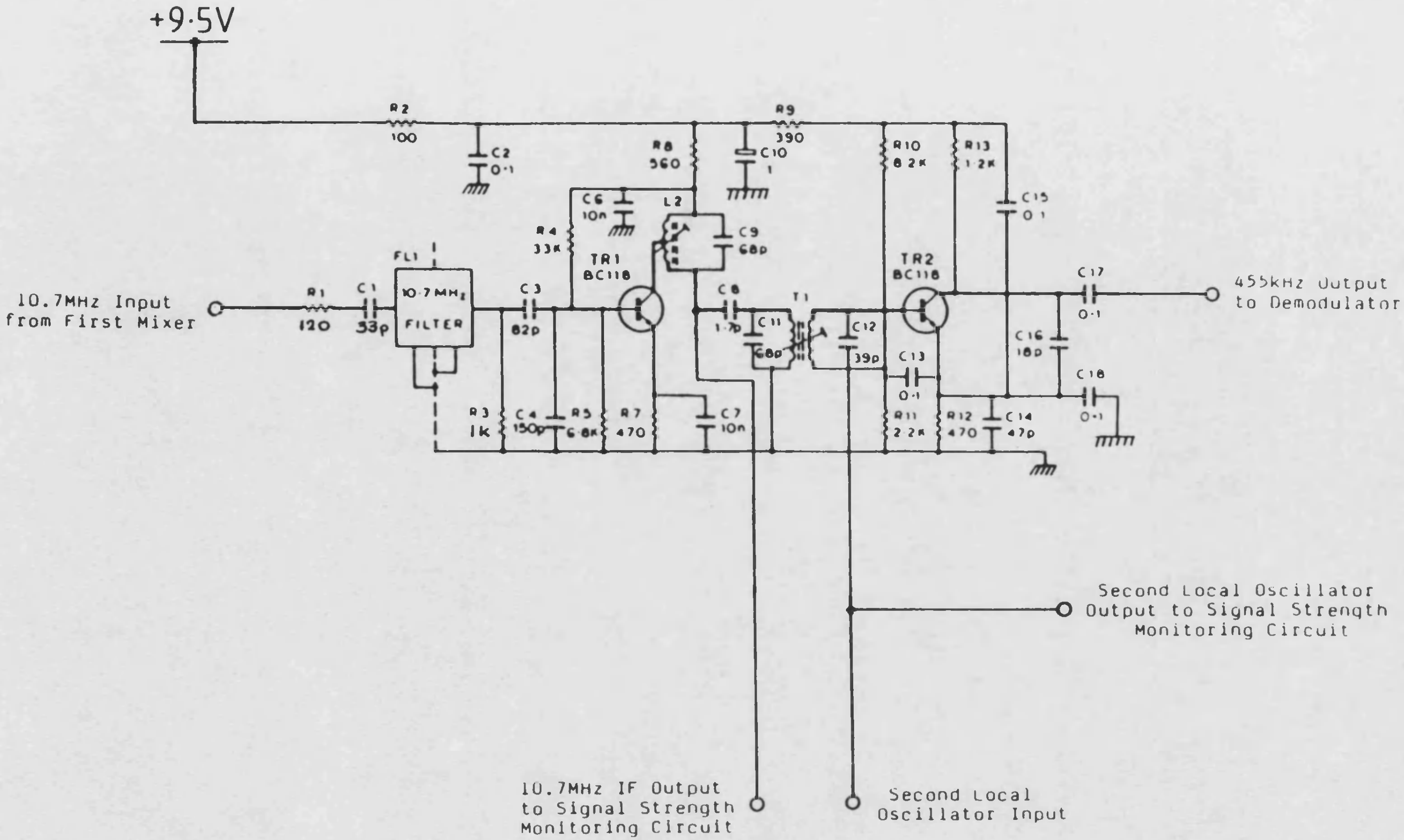


Figure 9.5. 10.7MHz IF Amplifier Stages of Mobile Receiver.

mobile transmitter, the circuit was constructed on a double sided printed circuit board with integral ground plane and enclosed in a screened box.

It is perhaps worth noting that modern mobile radio equipment would already possess signal strength monitoring capabilities thus reducing the additional hardware required to perform base station power control.

9.3.1.2 Tone Generator and Audio Combining Unit

The generation of the power control tone was achieved using the voltage controlled oscillator (VCO) section of an HEF4046B phase-locked loop integrated circuit. The VCO range, which is governed by a resistor/capacitor combination, was set to 1kHz whilst a second resistor provided the required VCO lower operating frequency limit of 4.0kHz, thus producing a power control tone which was variable in frequency between 4.0 and 5.0kHz.

Figure 9.6 shows the circuit diagram of the tone generation circuit together with the following audio combining stage. The output from the signal strength measuring circuit, after suitable scaling and filtering was applied directly to the VCO control input of the IC. The 4.0 to 5.0kHz output of the VCO was level

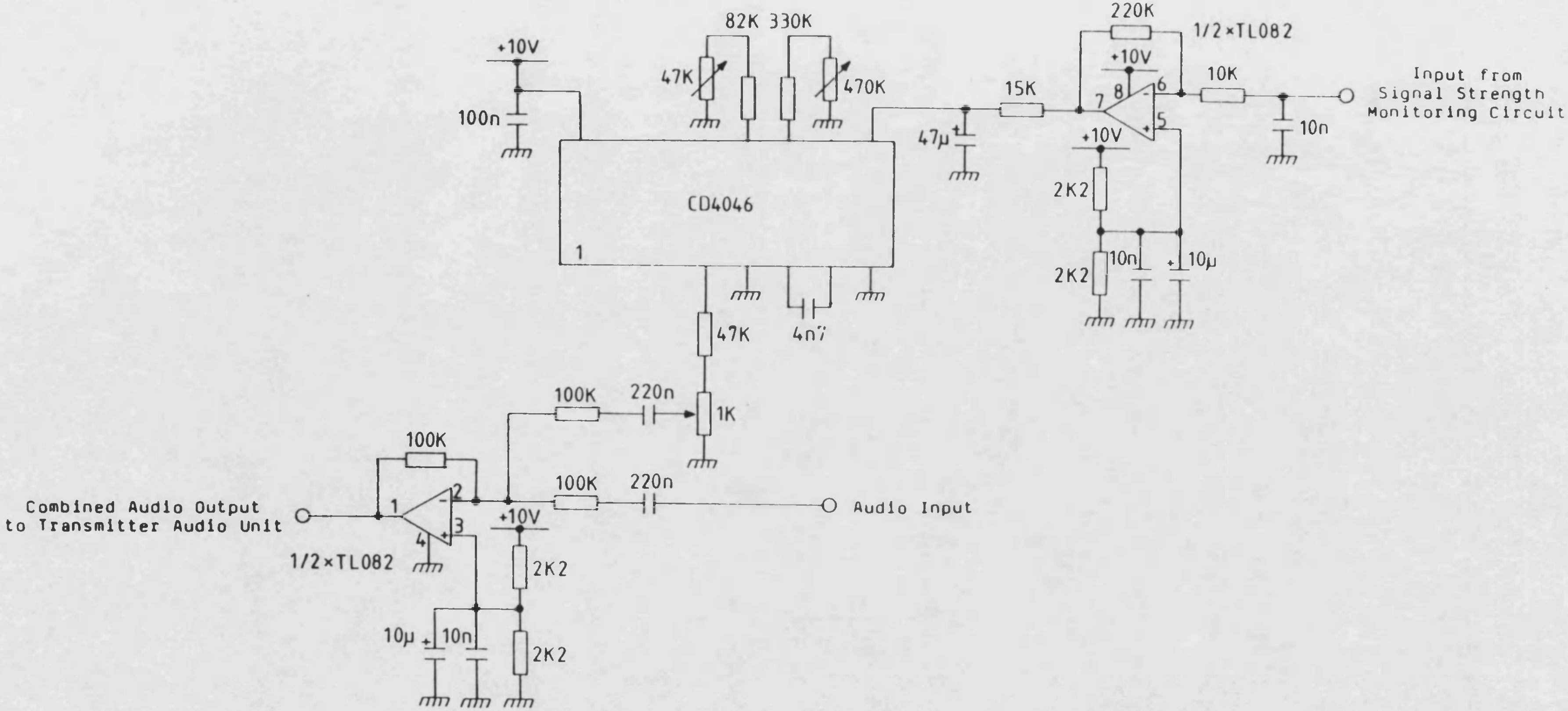


Figure 9.6. Tone Generator and Audio Combining Unit.

adjusted to provide the subsequently required ± 1.7kHz deviation at the output of the mobile transmitter (the frequency deviation used for tone signalling in TACS), prior to being added to the mobile transmit audio.

9.3.2 Base Station Power Control Circuitry

9.3.2.1 Power Control Tone Decoder

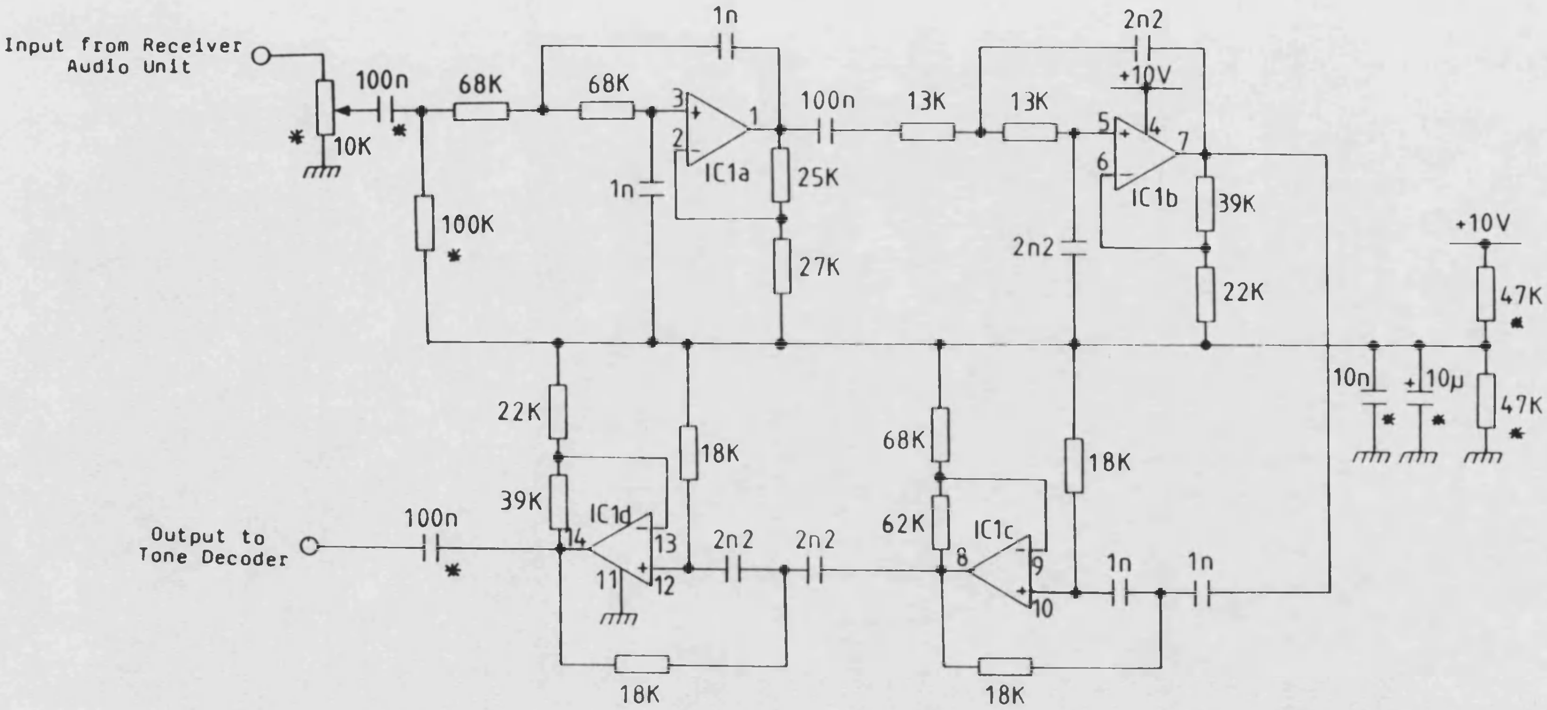
The power control tone decoding was performed using another phase-locked loop (PLL) IC, the XR-2211. Initial tests performed on the tone decoder showed that under conditions of low base station received signal levels, eg. less than 1µV p.d., the ability of the decoder to lock to the control tone was impaired. Also the presence of other signals at the input to the tone decoder, especially speech, sometimes caused the loop to become unlocked, and hence unreliable. To prevent these conditions occurring the power control tone was passed through a bandpass filter prior to application to the tone decoder unit. The circuit was also configured such that when the loop was unlocked or when the base station received signal level was too low to ensure reliable operation of the PLL, the base station output power was set to maximum. This was achieved through the use of a combination of the lock detect outputs of the XR-2211 and a control signal from the squelch unit of the receiver.

Figure 9.7 contains a circuit diagram of the bandpass filter, whilst Figure 9.8 gives the circuit diagram of the tone decoder unit. Figures 9.9 and 9.10 contain the circuit diagrams of the receiver audio unit and the squelch unit together with the interconnections to the tone decoding circuitry.

9.3.2.2 Voltage Controlled Power Amplifier

The voltage controlled power amplifier (VCPA) function was achieved by locating a pin diode attenuator between the modulator/driver and power amplifier of the transmitter. This attenuator was capable of providing up to 35dB of attenuation, which when coupled with the non-linear gain characteristic of the class C power amplifier within the equipment, resulted in a possible maximum base station power control range in excess of 60dB. The pin diode attenuator, which had a 2.5dB insertion loss, was immediately followed by a linear amplifier with a similar gain so as to maintain the same maximum base station transmitter power as that prior to modification.

The circuit diagrams of the pin diode attenuator and linear amplifier are shown in Figures 9.11 and 9.12 respectively. Gain and offset controls enabled the



IC1 - LM324
All Resistors and Capacitors are 1% Tolerance Except Those Starred

Figure 9.7. Power Control Tone Bandpass Filter.

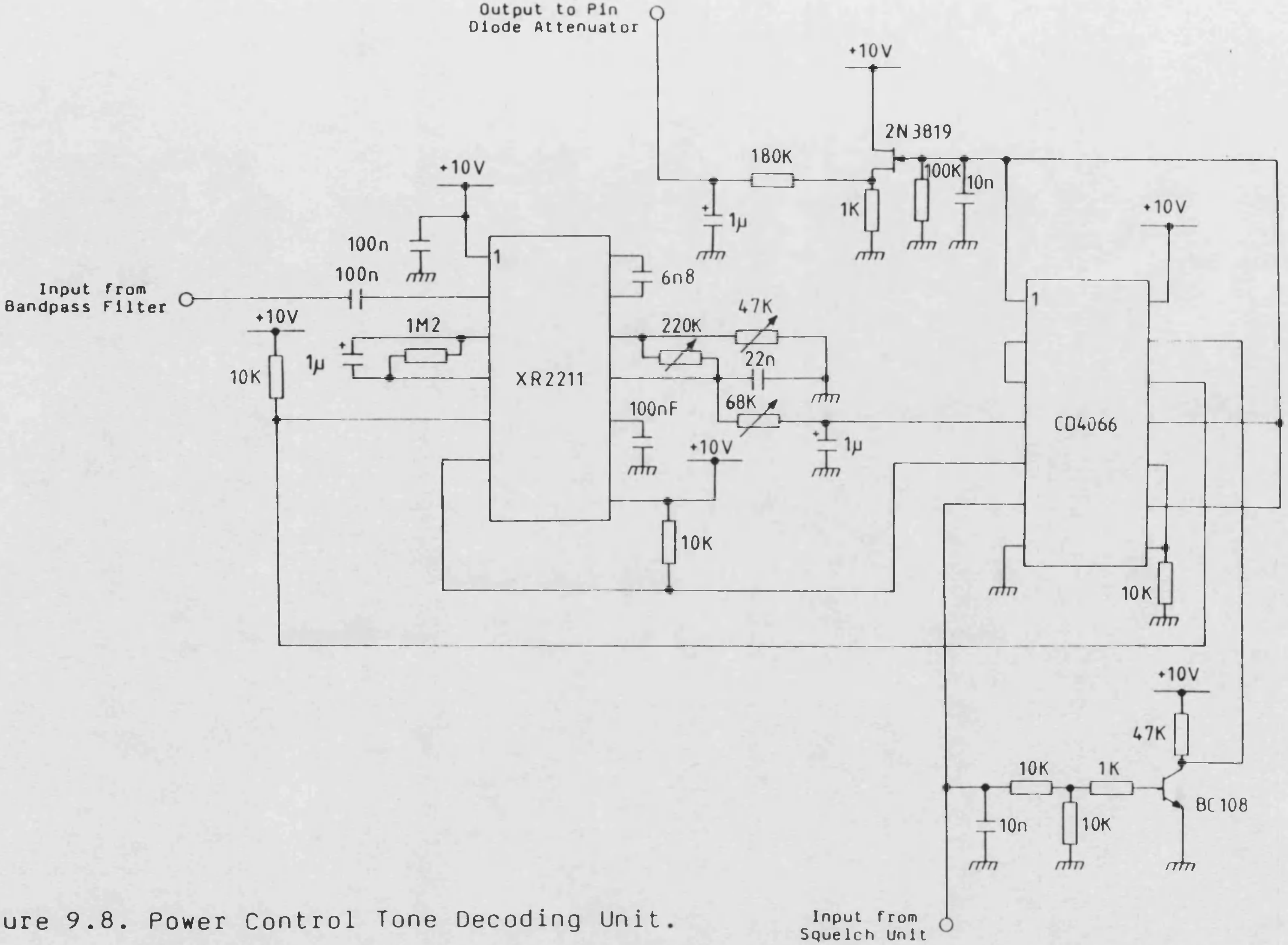


Figure 9.8. Power Control Tone Decoding Unit.

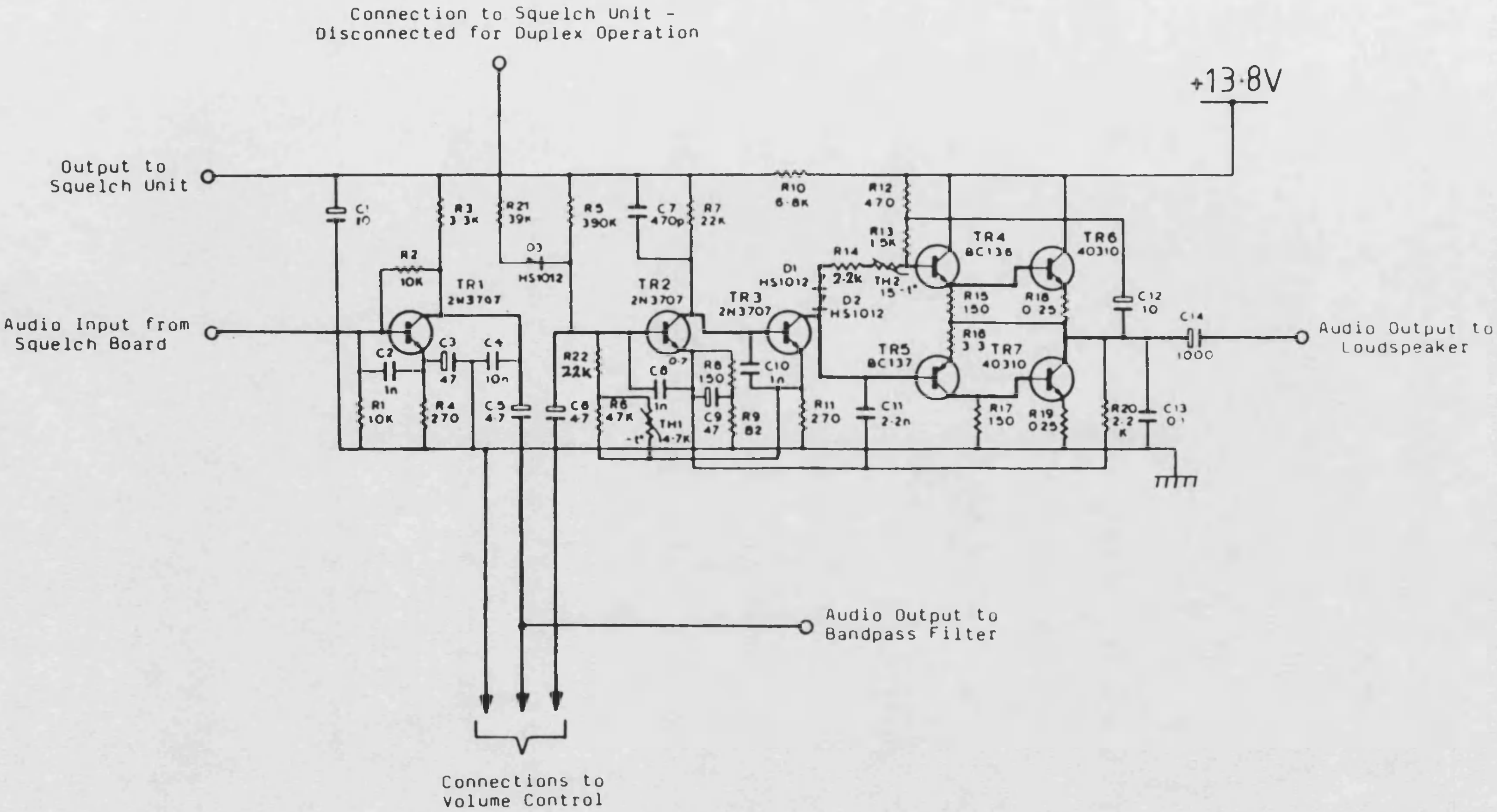


Figure 9.9. Base Station Receiver Audio Unit.

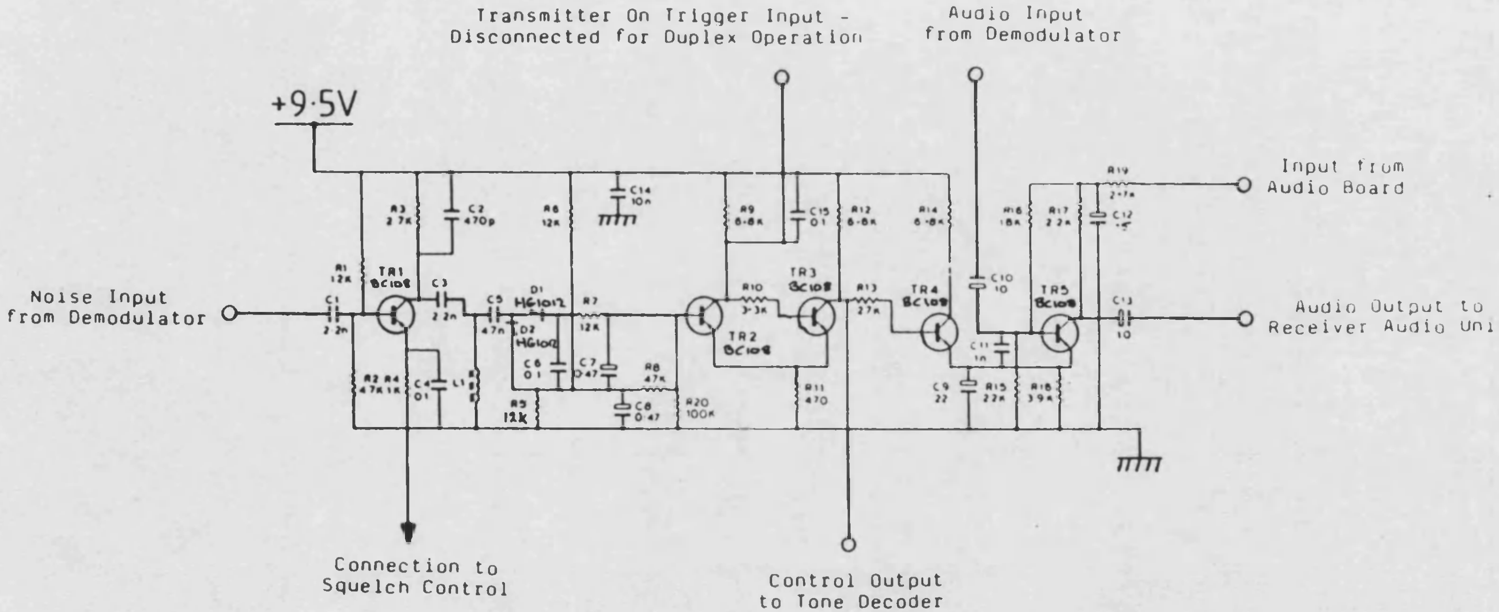


Figure 9.10. Base Station Receiver Squelch Unit.

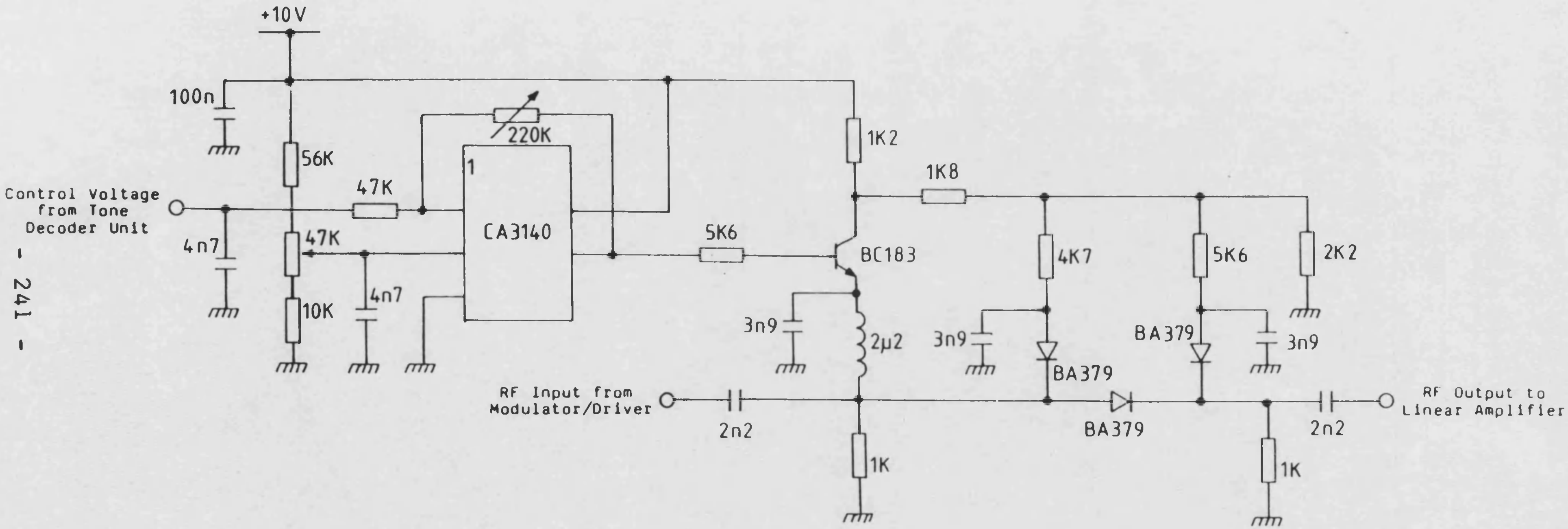
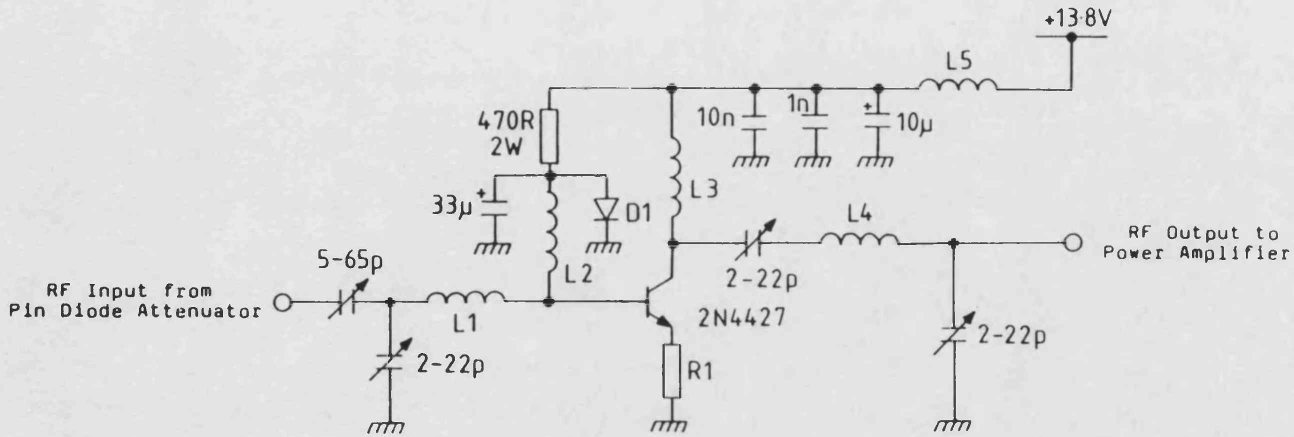


Figure 9.11. Pin Diode Attenuator.



D1 - 1N4001 in Thermal Contact with Transistor
R1 - 2.2Ω 1W Carbon Composition

L1 - 2 Turns 16SWG 3/16" Internal Diameter 1/4" Long
L2 - Ferrite Choke Z=450Ω
L3 - 2 Turns 16SWG 1/4" Internal Diameter 1/4" Long
L4 - 1.5 Turns 16SWG 3/8" Internal Diameter 3/8" Long
L5 - As L2

Figure 9.12. Linear Amplifier.

control voltage obtained from the power control tone decoder circuit to provide the required base station power control range, which for the purpose of this investigation was set to 45dB, thus giving maximum and minimum base station output powers of 3.5W and 100μW respectively.

A separate 10V regulated dc supply was also installed into both transceivers from which all power control circuits except the linear amplifier in the base station were run. Figure 9.13 shows a circuit diagram of the regulation circuit.

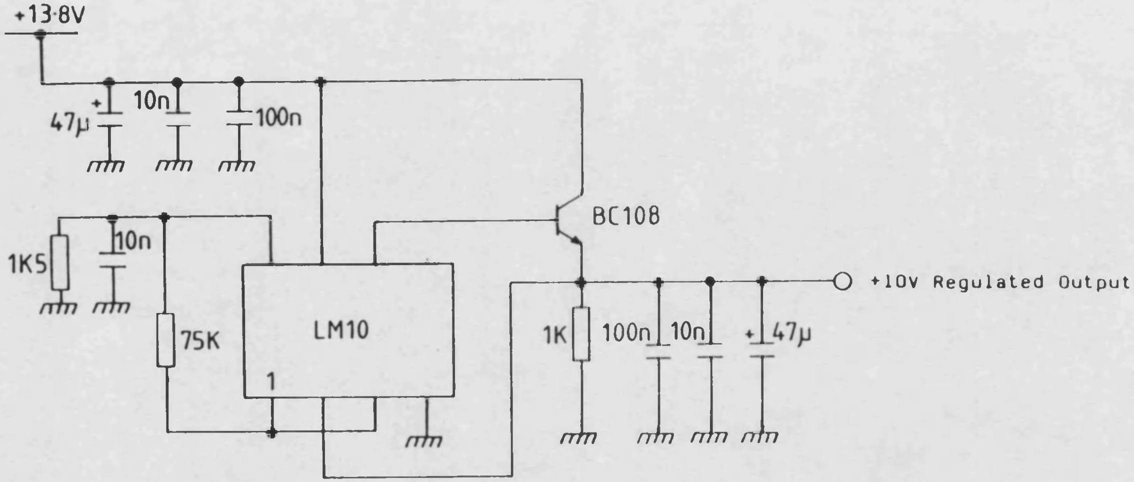


Figure 9.13. 10V Regulator Unit.

9.4 TESTING AND EVALUATION OF THE POWER CONTROL SYSTEM

Initial testing and evaluation of the power control system was performed on the bench using switchable attenuators to simulate variations in mobile-base station separation and a voltage controlled attenuator to simulate shadowing losses. From these early investigations, it was decided to operate the power control system with the aim of limiting the fluctuations in mobile received signal strength caused by path loss and shadowing propagation characteristics to less than 10dB. Since the idea behind the power control system is to maintain the desired signal quality at the mobile whilst using the minimum necessary base station transmitter power, the demodulation characteristics of the mobile receiver were used to obtain the exact point at which commencement of base station power reduction would occur. The SINAD curve for the mobile transceiver is shown in Figure 9.14, from which it can be seen that mobile received signal levels in excess of -100dBm (2.2μV p.d.) gave rise to no further improvement in the quality of the demodulated signal. Such received signal levels are therefore unnecessary, and so it was at this point that the power control system was set up to begin the reduction in base station output power. The minimum level of output power was set to correspond to

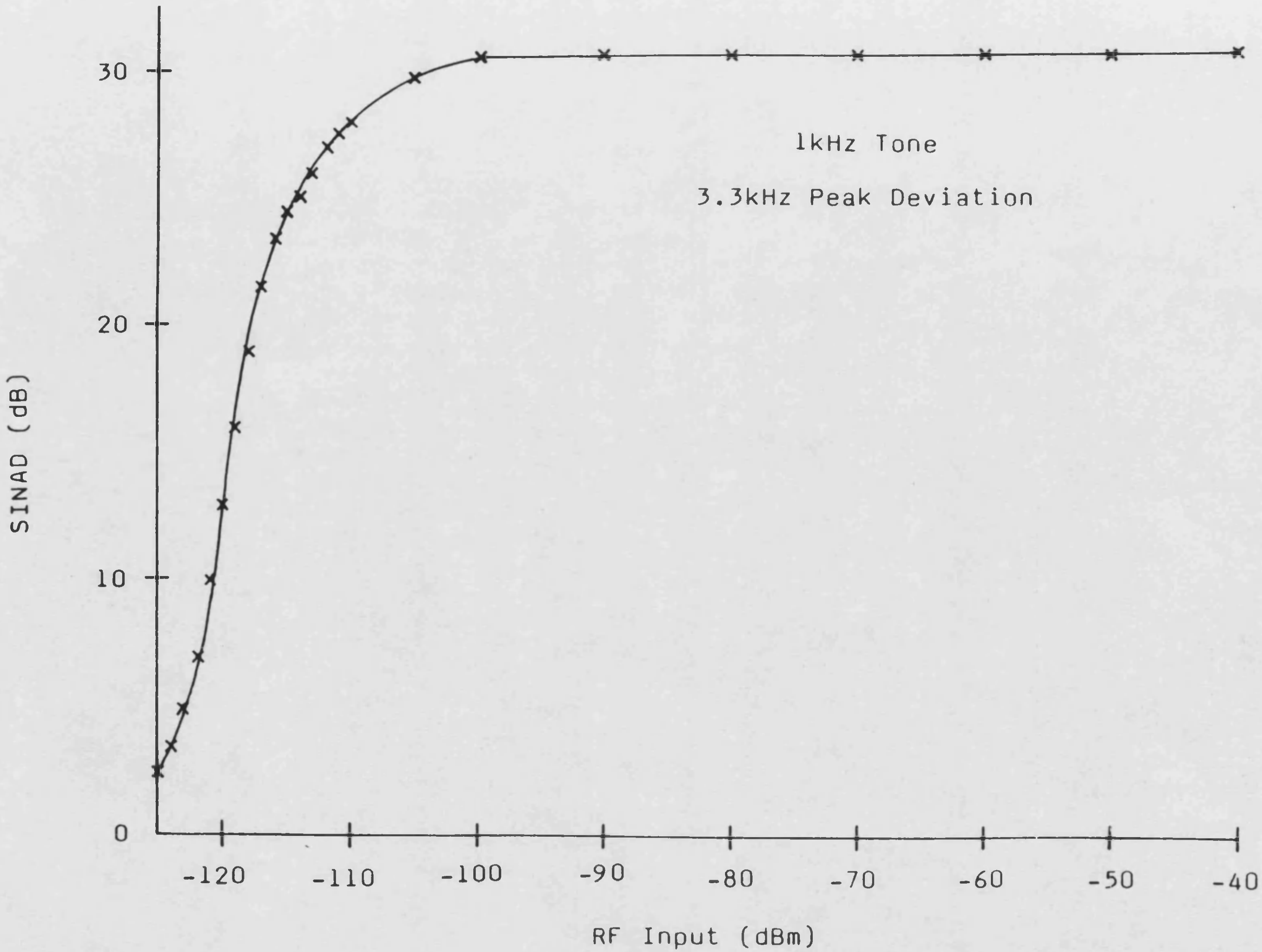


Figure 9.14. SINAD Curve for Mobile Receiver.

a mobile received signal level of more than -90dBm (7.0μV p.d.), thus providing the required window of 10dB in which the mobile signal level was to be kept. The exact characteristics of the power control system are shown in Figures 9.15 to 9.19. The transient responses of the base station and mobile power control circuitry show that the system is slow enough to ensure that fast fading does not affect the power control scheme in any way, whilst quick enough to provide significant correction for shadow losses. The difference in the response times for the low to high power and high to low power transitions of the base station power control circuitry can be explained by the PLL's inability to follow sudden steps in power control tone. The configuration of the power control circuitry such that maximum power is transmitted whilst the tone decoder is unlocked results in a quicker low to high change in output power than for a high to low power change.

Final evaluation of the power control scheme consisted of performing numerous field trials on the system. The base station transceiver was operated into two separate, but identical antennae located on the roof of the building. The mobile transceiver operated, in conjunction with a duplexer, into a single quarter wavelength whip antenna mounted on the roof of the test

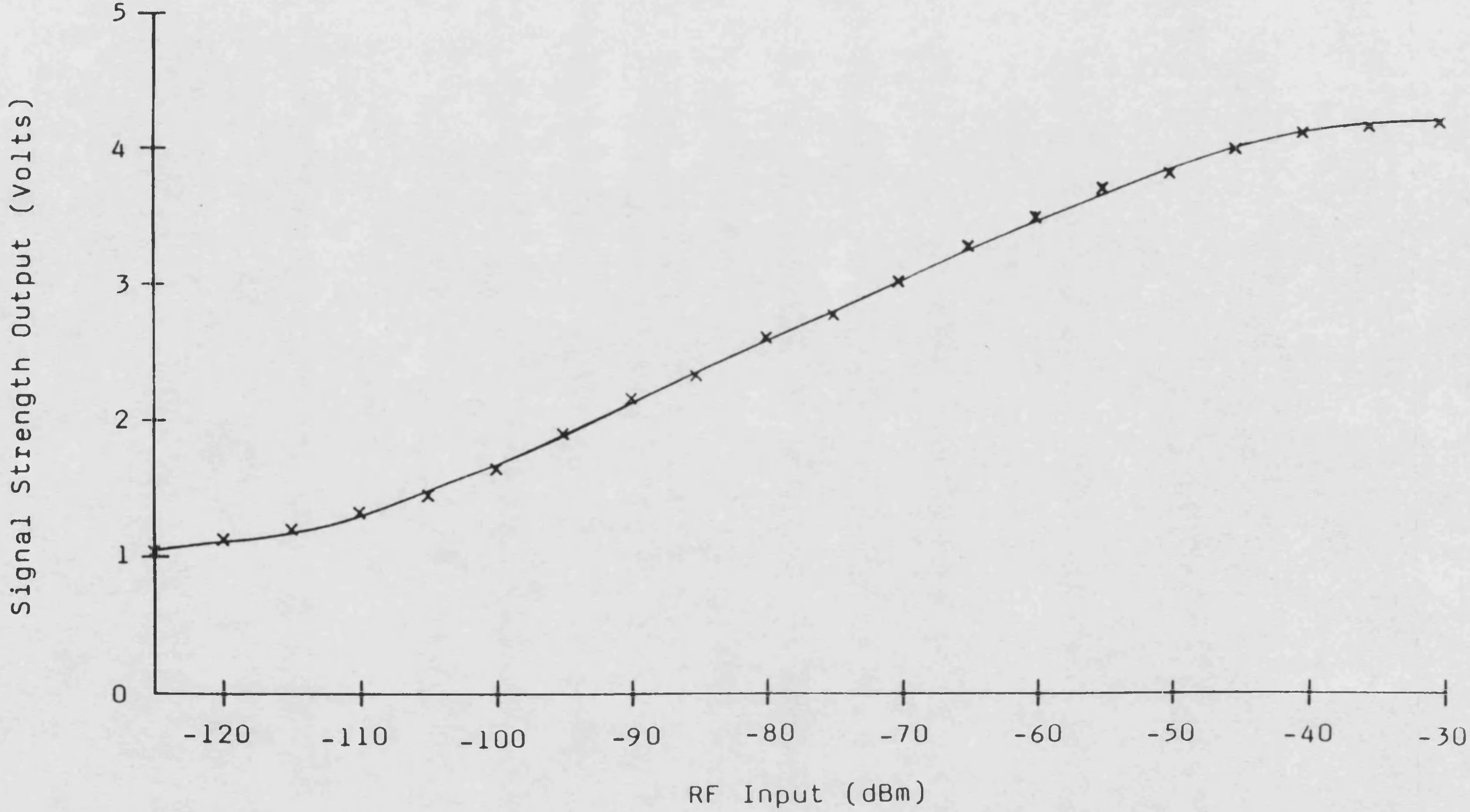


Figure 9.15. Signal Strength Characteristic of Mobile Receiver.

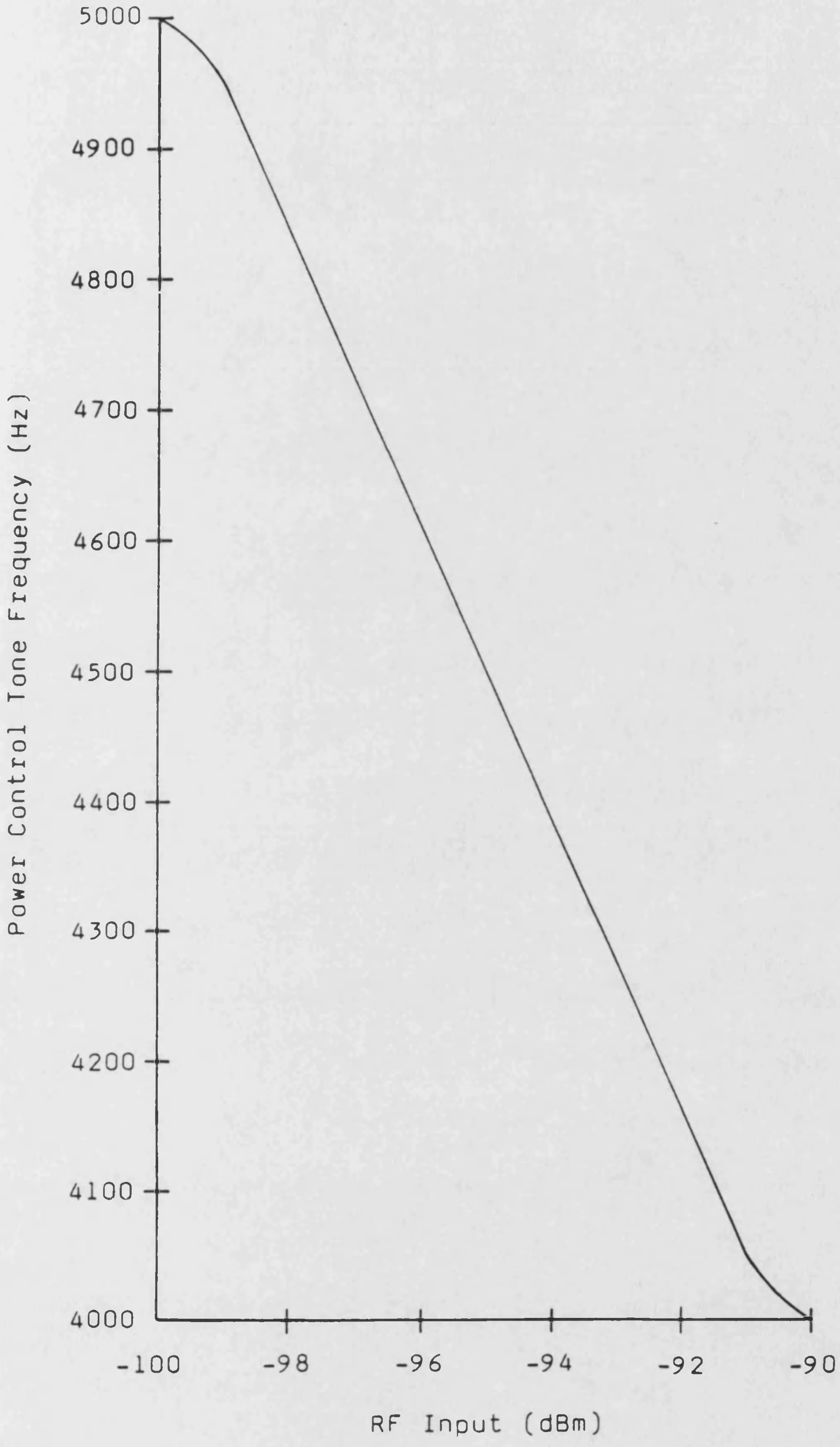


Figure 9.16. Power Control Tone Characteristic.

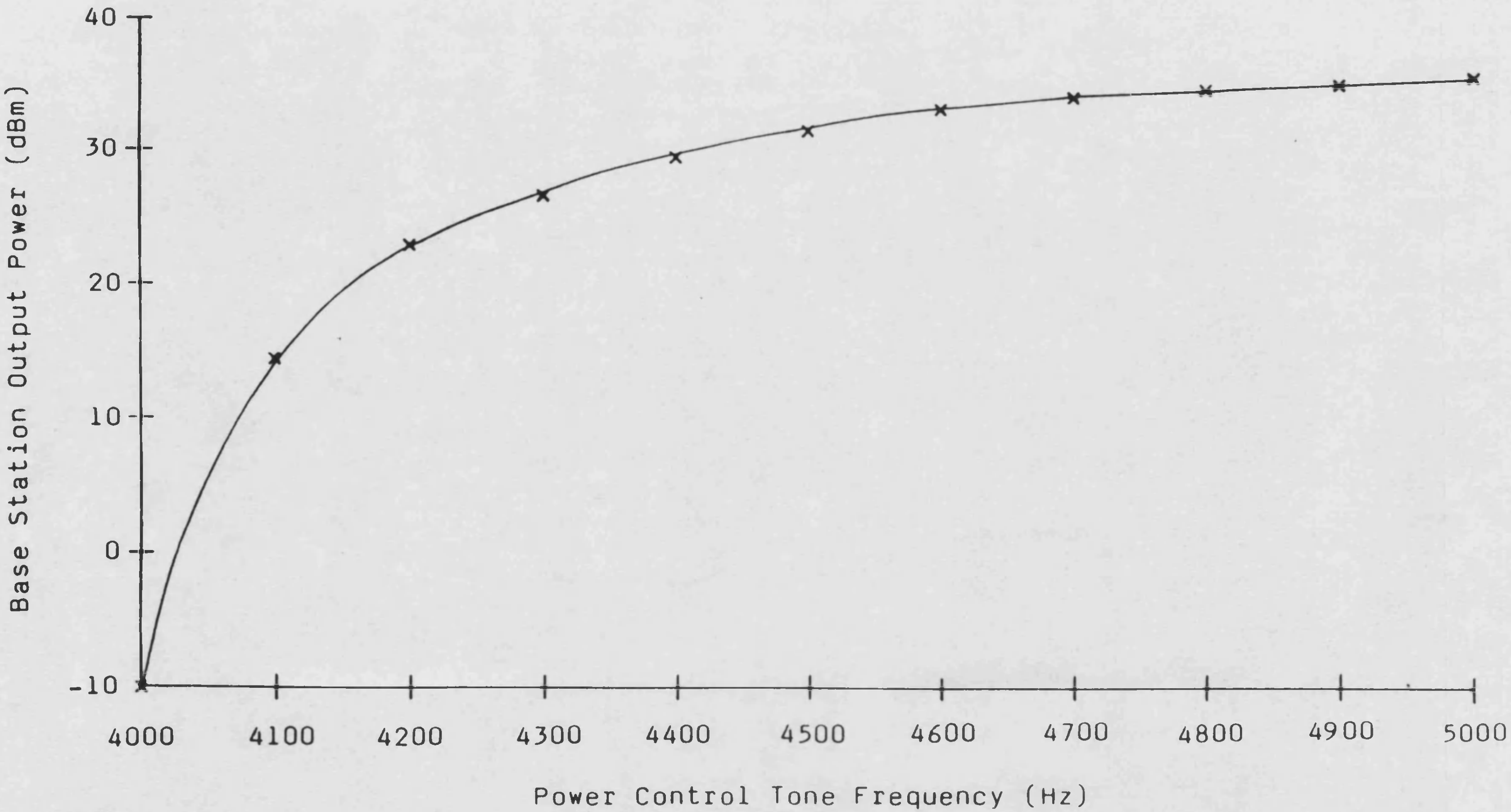


Figure 9.17. Base Station Power Output Characteristic.

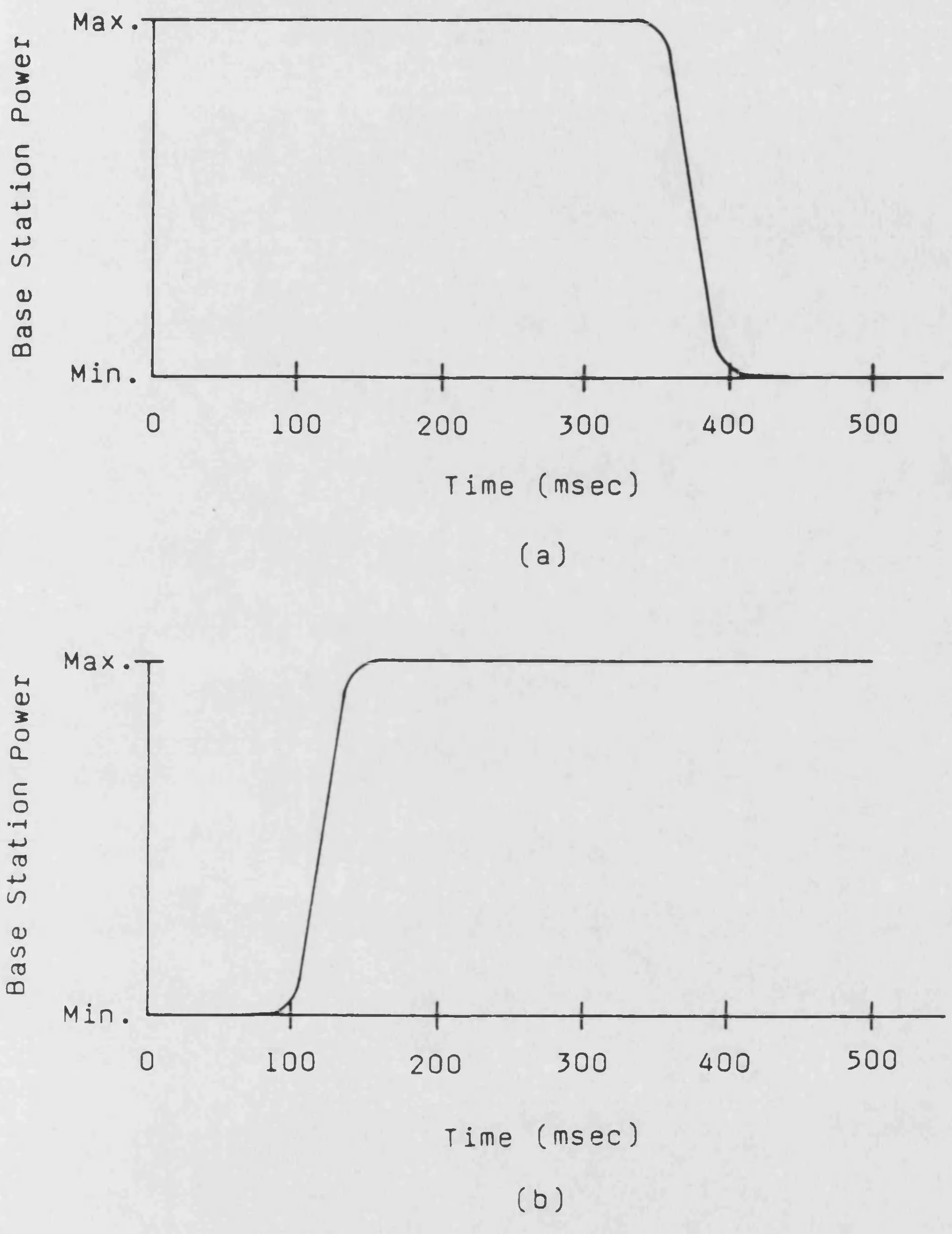


Figure 9.18. Step Response of Base Station Power Control Circuitry.

(a) High Power to Low Power

(b) Low Power to High Power

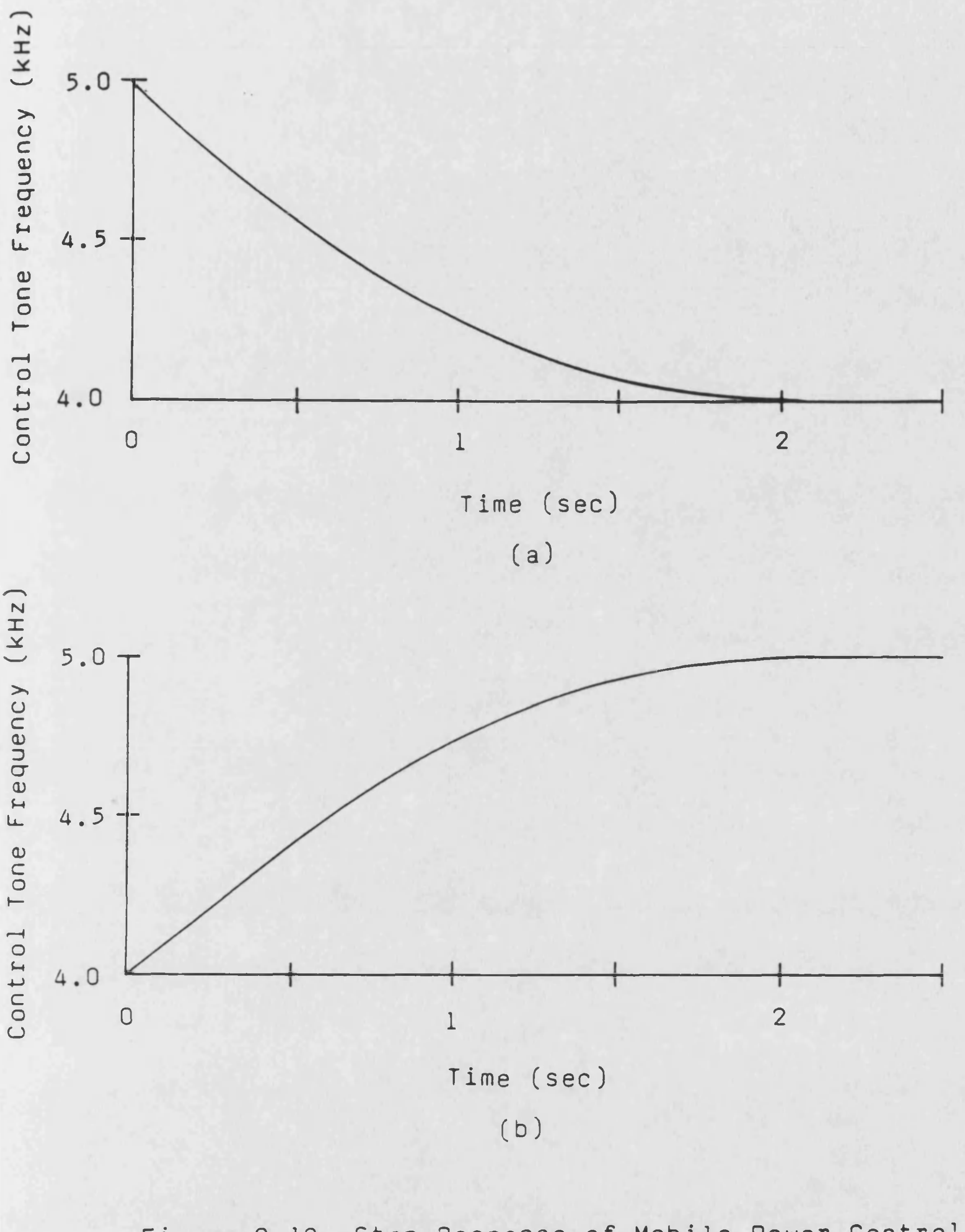


Figure 9.19. Step Response of Mobile Power Control Circuitry.

(a) Low Signal Level to High Signal Level

(b) High Signal Level to Low Signal Level vehicle. The duplexer was constructed using six notch filters (band-reject cavities), three in each branch. The three cavities situated between the transmitter output and the aerial resulted in a 74dB attenuation in transmitter noise at the receive frequency, whilst the three located between the receiver input and the antenna gave 76dB of attenuation at the transmitter frequency thus avoiding receiver desensitisation. The corresponding transmitter to antenna insertion loss was 1dB, whilst the insertion loss, receiver to antenna, was slightly higher at 1.5dB.

The field trials carried out on the system consisted of performing two distinct sets of measurements, namely the measurement of mobile received signal strength over test routes, firstly without base station power control, and then the measurement of received mobile signal level and corresponding base station output power over the same test routes with the power control system in operation. This entailed the continuous recording of mobile received signal level over the test routes, and for the power control case, a simultaneous recording of the corresponding base station output power. The recording of the mobile received signal level was achieved using a portable computer connected through the necessary interface circuitry to the signal strength indicator of the mobile receiver. Readings of received signal strength were taken regularly at 10 metre intervals along the test routes through the use of a distance transducer connected to the speedometer of the test vehicle. The distance information was also conveyed back to the base station over the mobile transmit channel through the use of frequency shift keying (FSK) techniques, where it was stored on an instrumentation tape recorder together with the corresponding value of base station output power. On completion of the field trials, the information stored on the tape was read into the portable computer and then uploaded onto the main computer for further analysis. The circuit diagrams of the hardware built for this testing and evaluation of the power control system are given in appendix B on page 289.

To enable the mobile signal strength to be measured over a test route for both power control and no power control test conditions necessitated the test vehicle to be driven twice along each route. In order to ensure that the test runs with and without power control were performed under as similar conditions as possible, and that the results obtained were in no way dependent on the relative motion of the test vehicle, the test runs were carried out at constant speed. This did however restrict the test routes over which to perform the field trials to roads on which constant speed travel was possible.

The use of geographical markers to identify the start and stop points of each test route allowed synchronisation between power control and non-power control runs to be achieved to within approximately 2 metres.

The field trials were performed over three different test routes at speeds ranging between 30mph and 50mph. Figure 9.20 shows the geographical location of the three test routes together with that of the base station. The results obtained are presented in Figures 9.21 to 9.30. The first graph of each figure shows the received mobile signal strength recorded over a test route both with and without the base station power control system in operation. The second graph shows the corresponding variation in the base station output power for the test run performed with base station power control.

A direct comparison between results obtained from runs performed with power control and without power control over a test route is somewhat meaningless since, by the very nature that they were not obtained

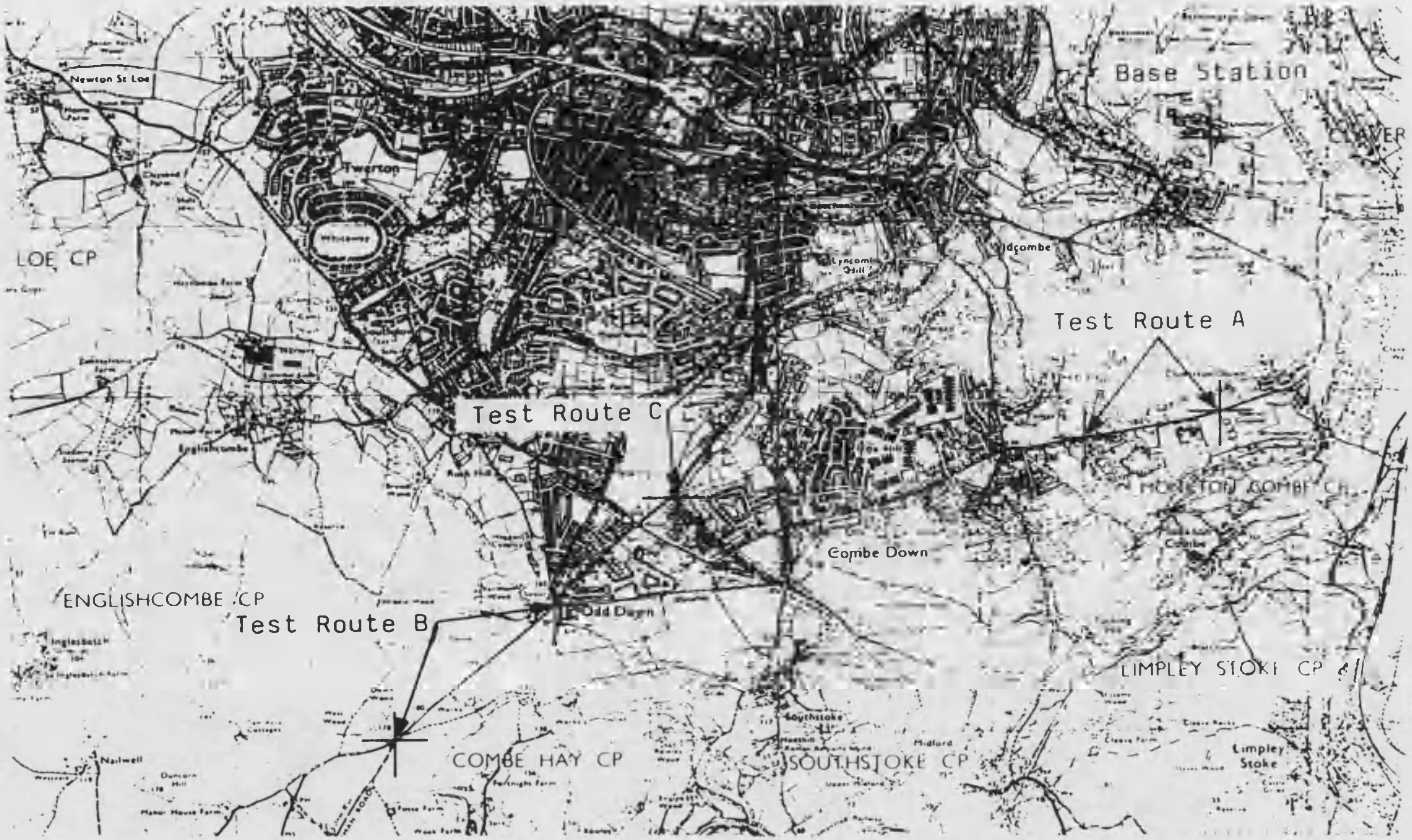


Figure 9.20. Geographical Location of Test Routes and Base Station.

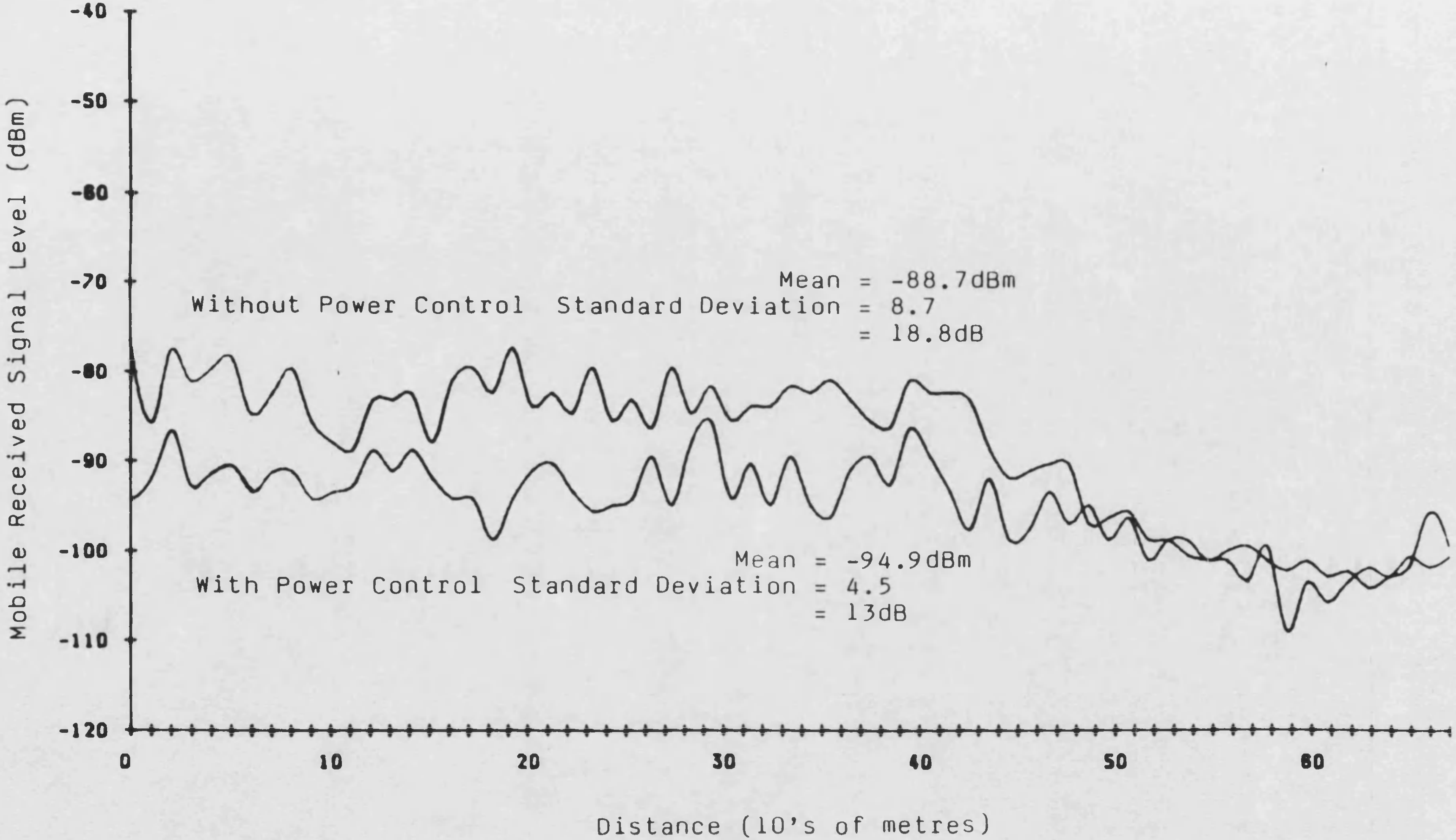


Figure 9.21a. Mobile Received Signal Level for Test Route A at 30mph.

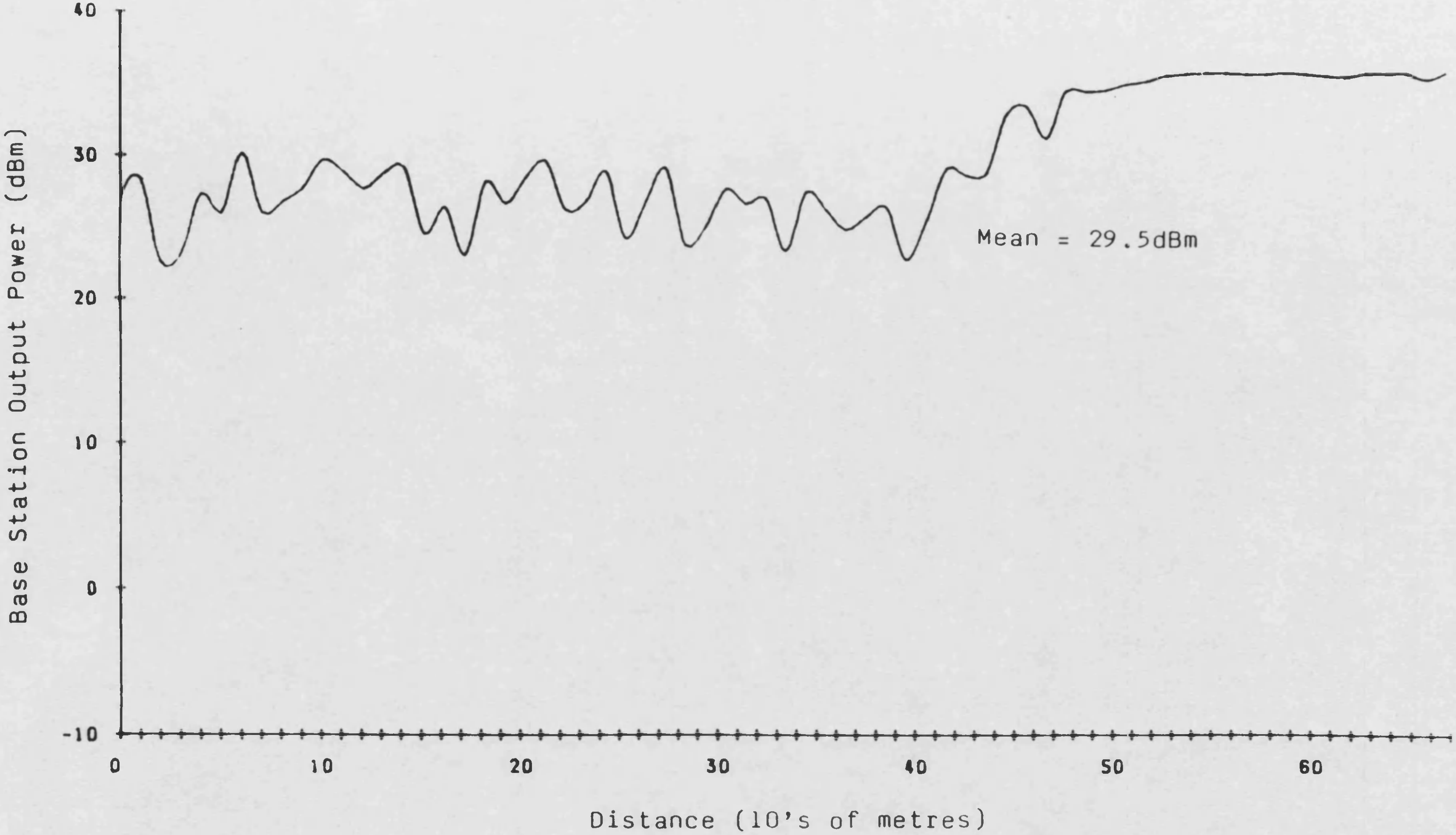


Figure 9.21b. Base Station Output Power for Test Route A at 30mph.

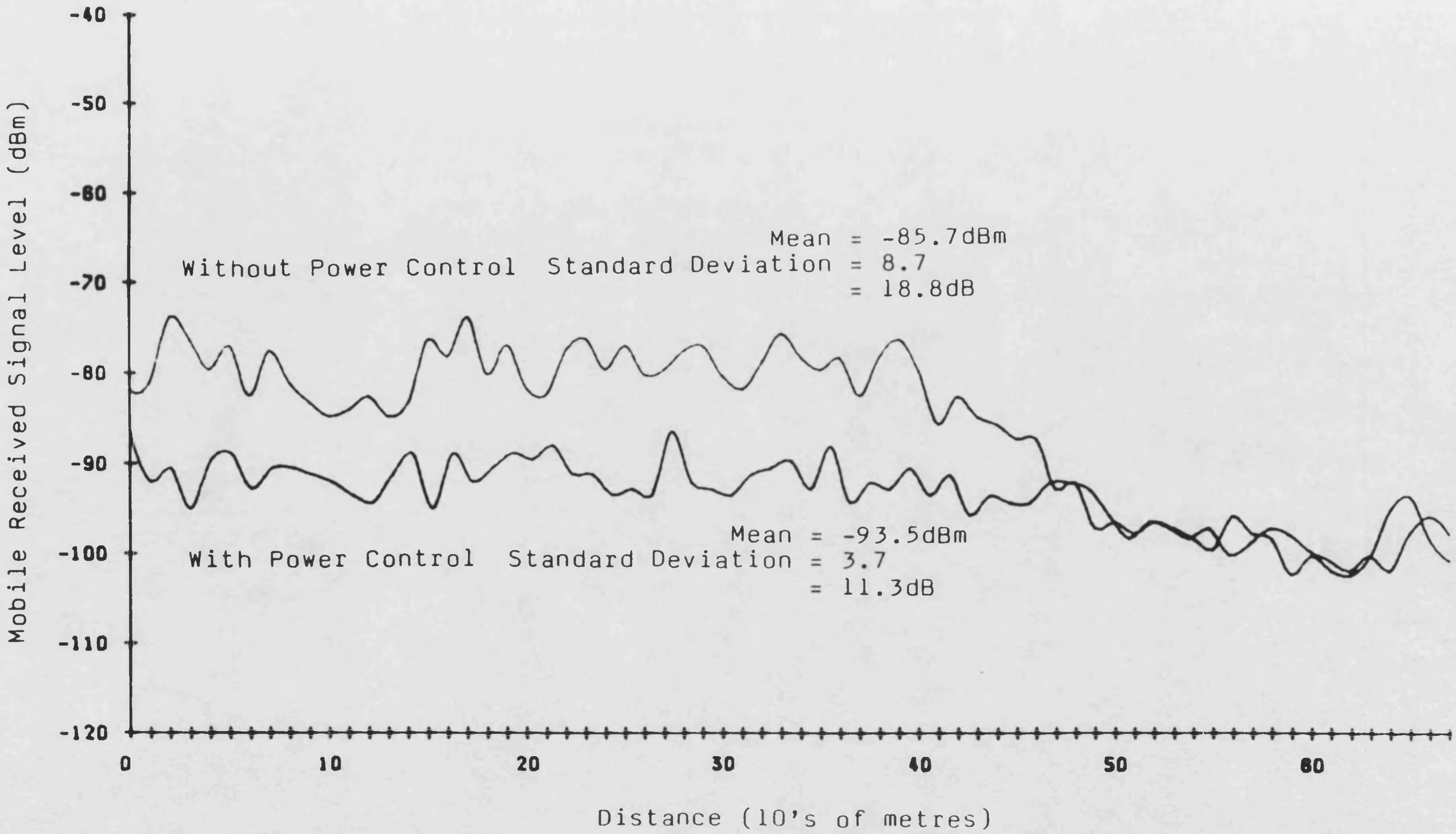


Figure 9.22a. Mobile Received Signal Level for Test Route A at 40mph.

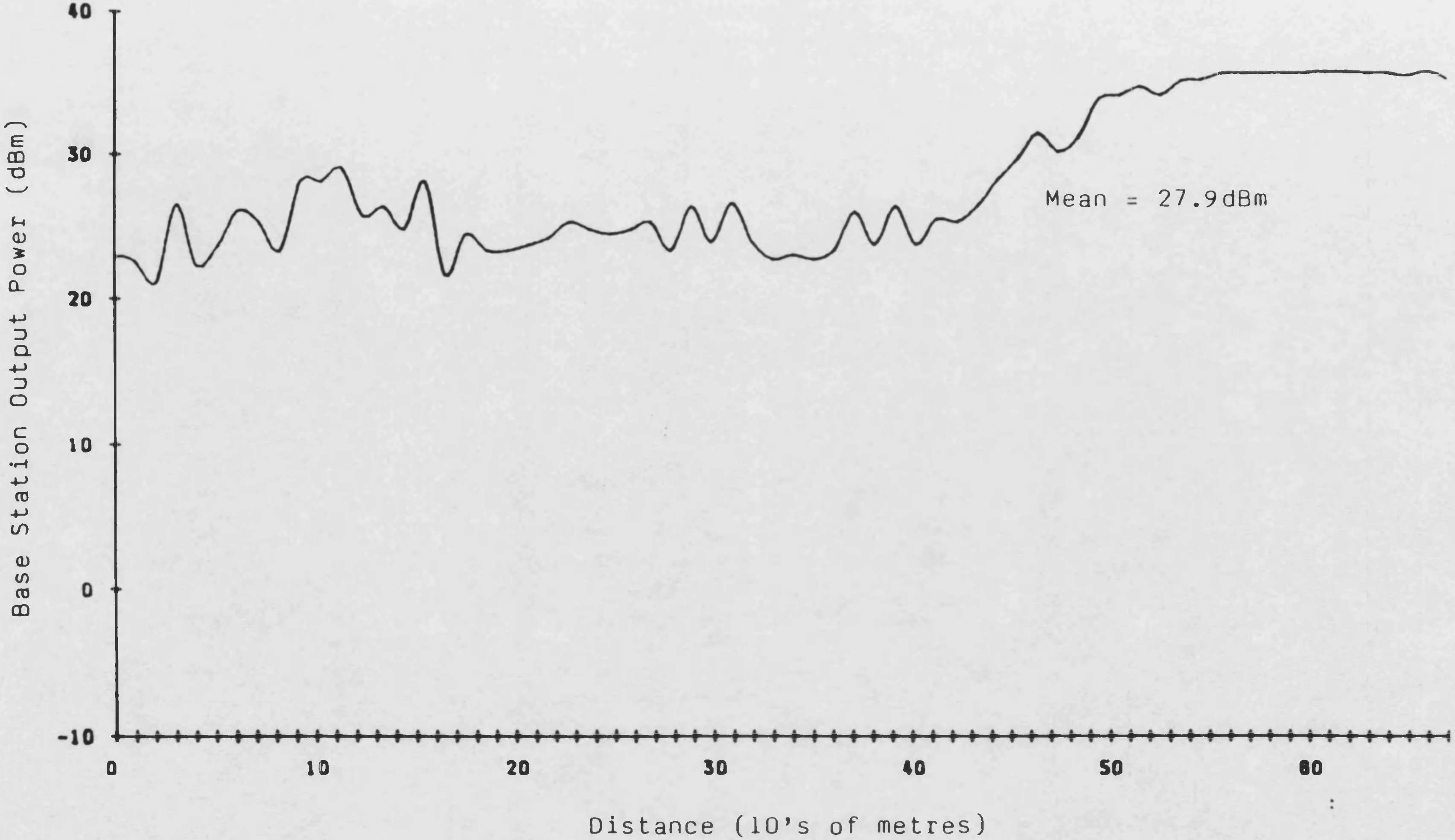


Figure 9.22b. Base Station Output Power for Test Route A at 40mph.

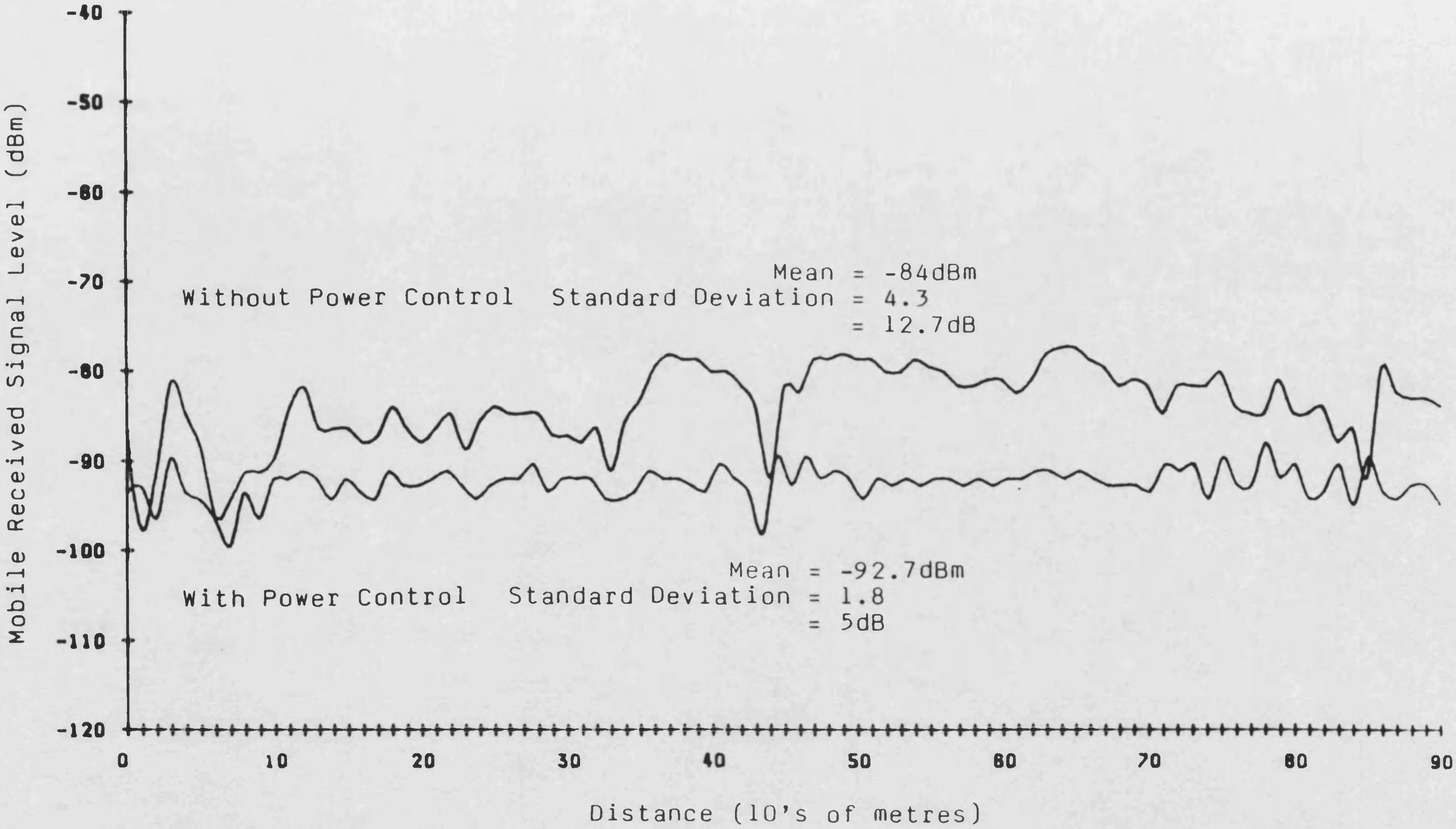


Figure 9.23a. Mobile Received Signal Level for Test Route B at 30mph.

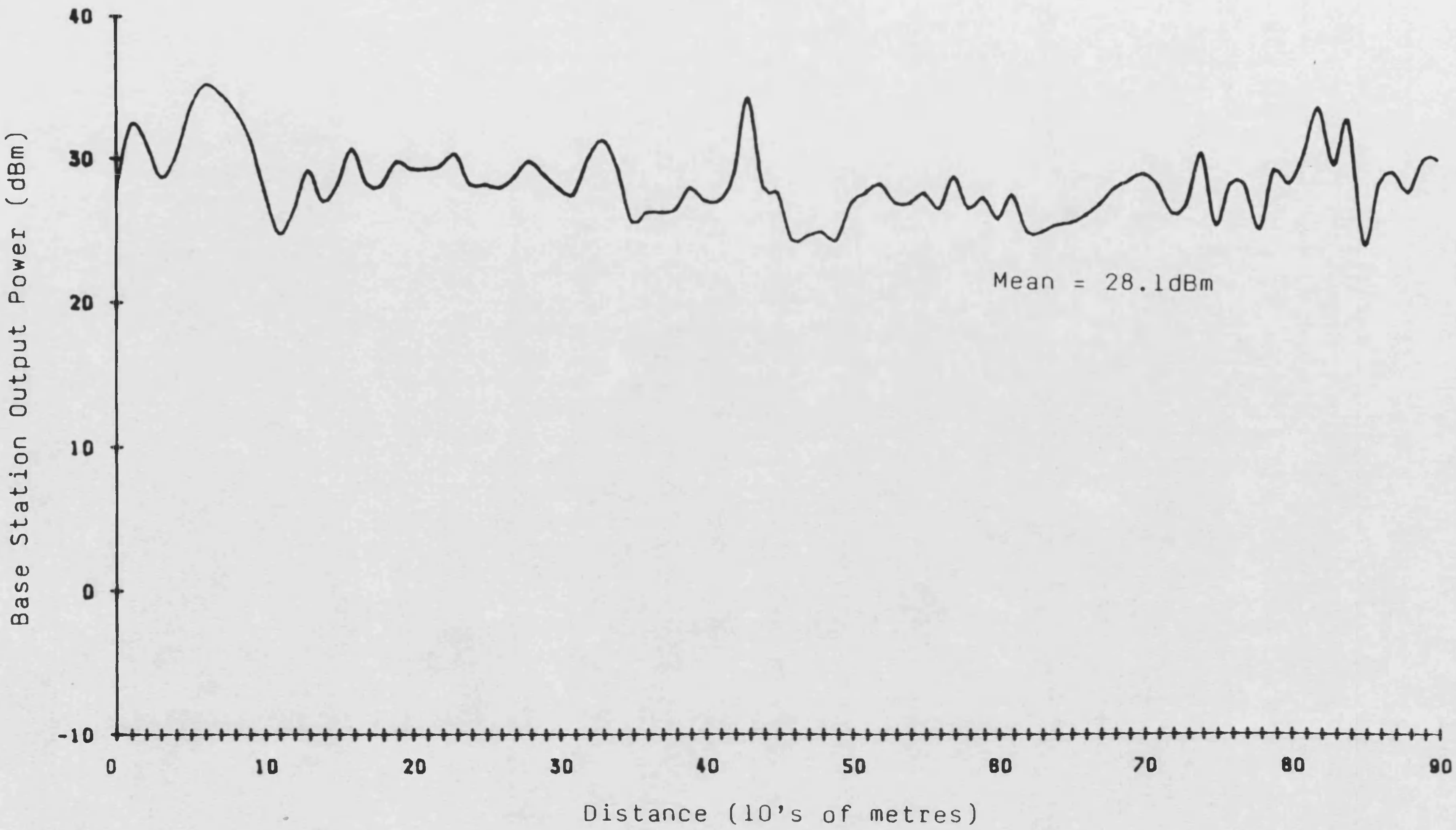


Figure 9.23b. Base Station Output Power for Test Route B at 30mph.

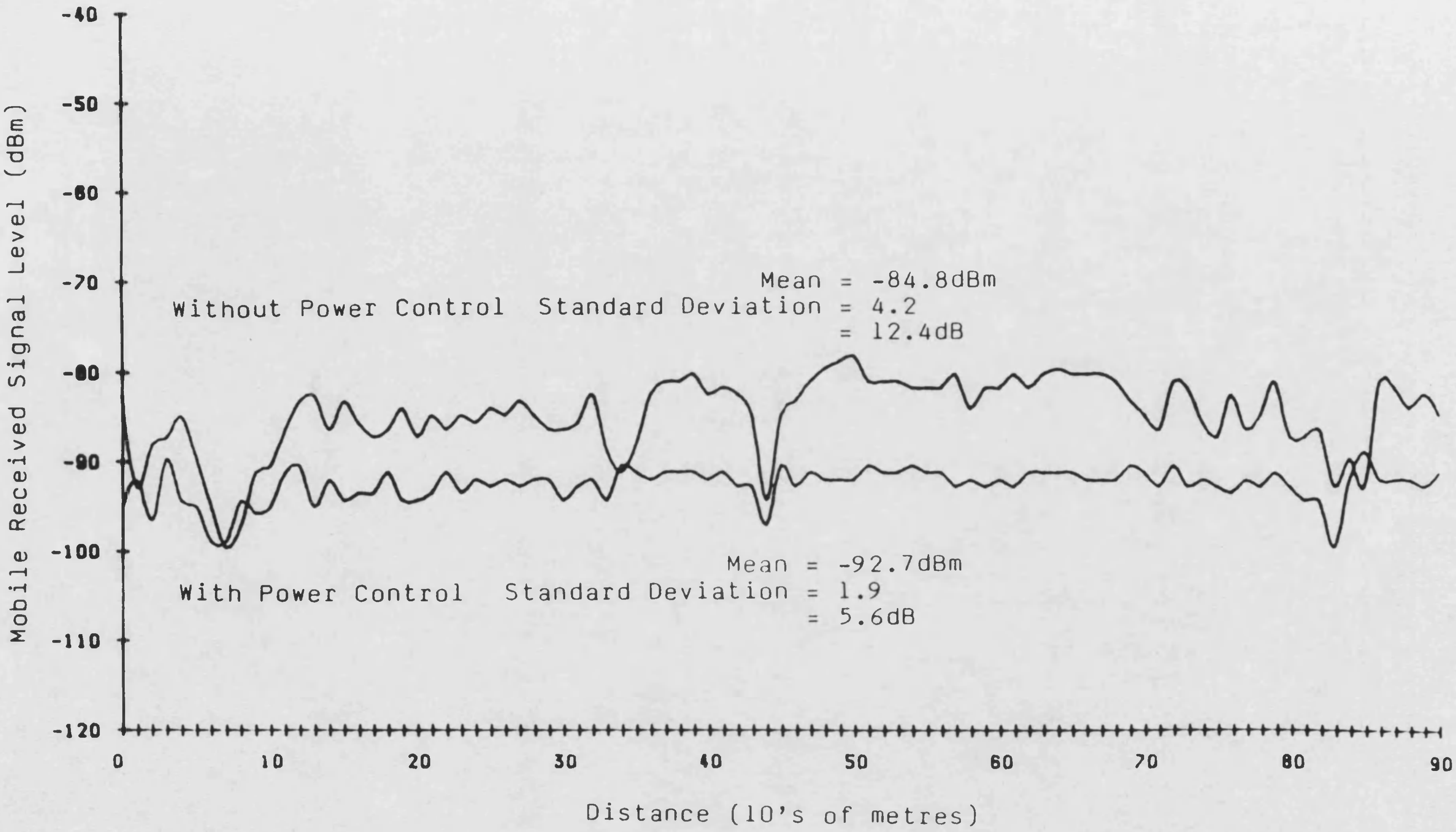


Figure 9.24a. Mobile Received Signal Level for Test Route B at 40mph.

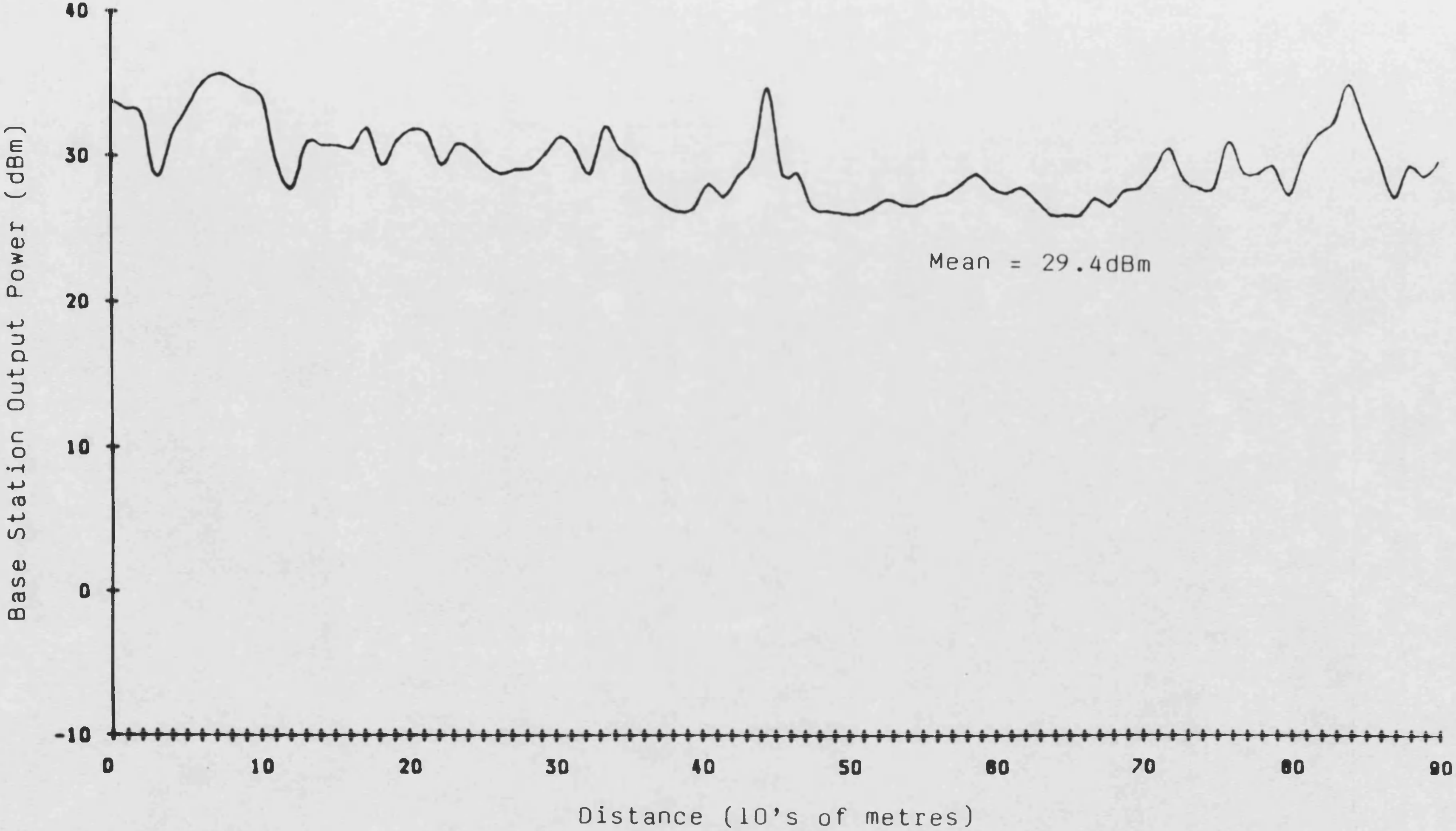


Figure 9.24b. Base Station Output Power for Test Route B at 40mph.

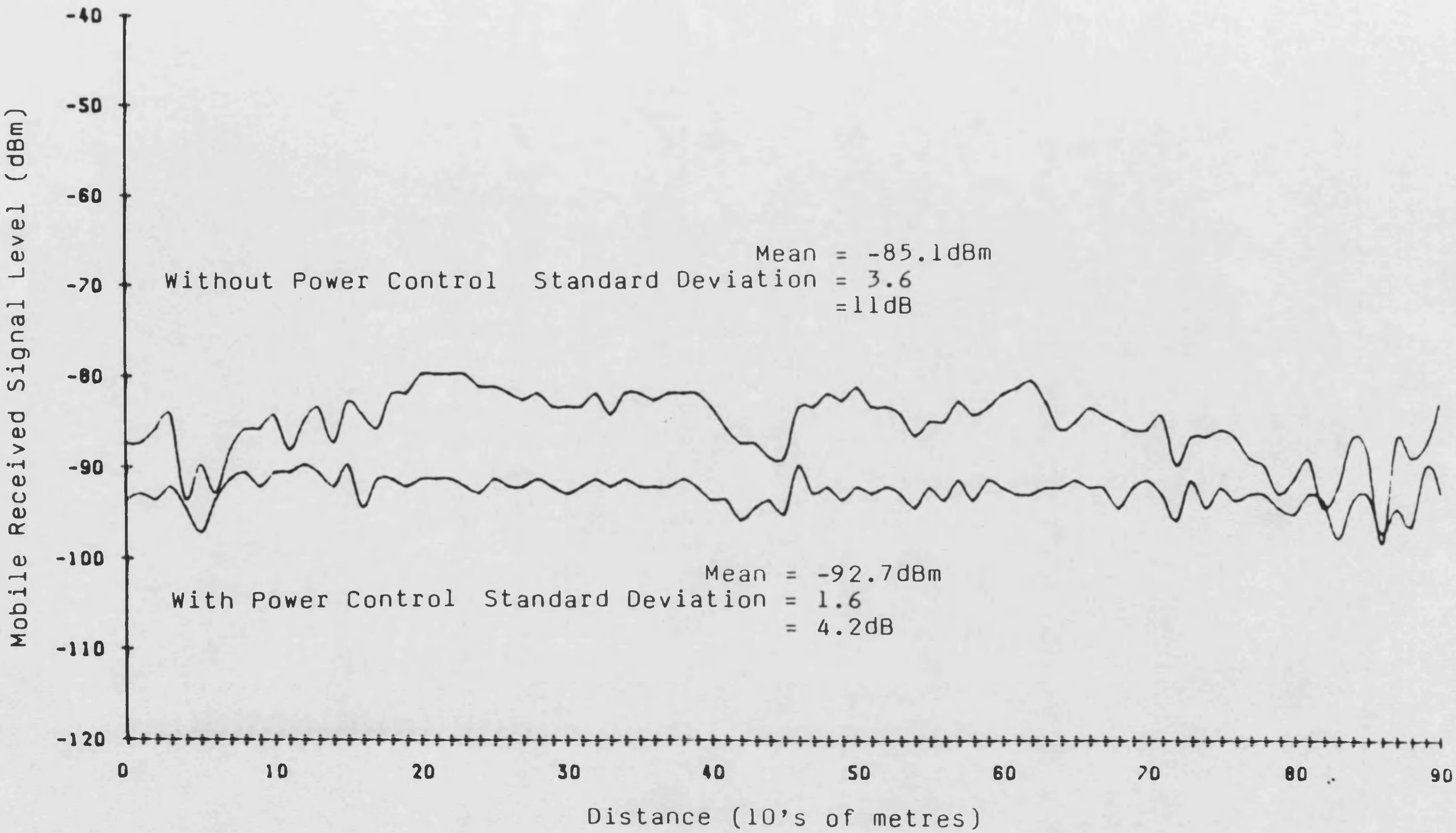


Figure 9.25a. Mobile Received Signal Level for Test Route B at 50mph.

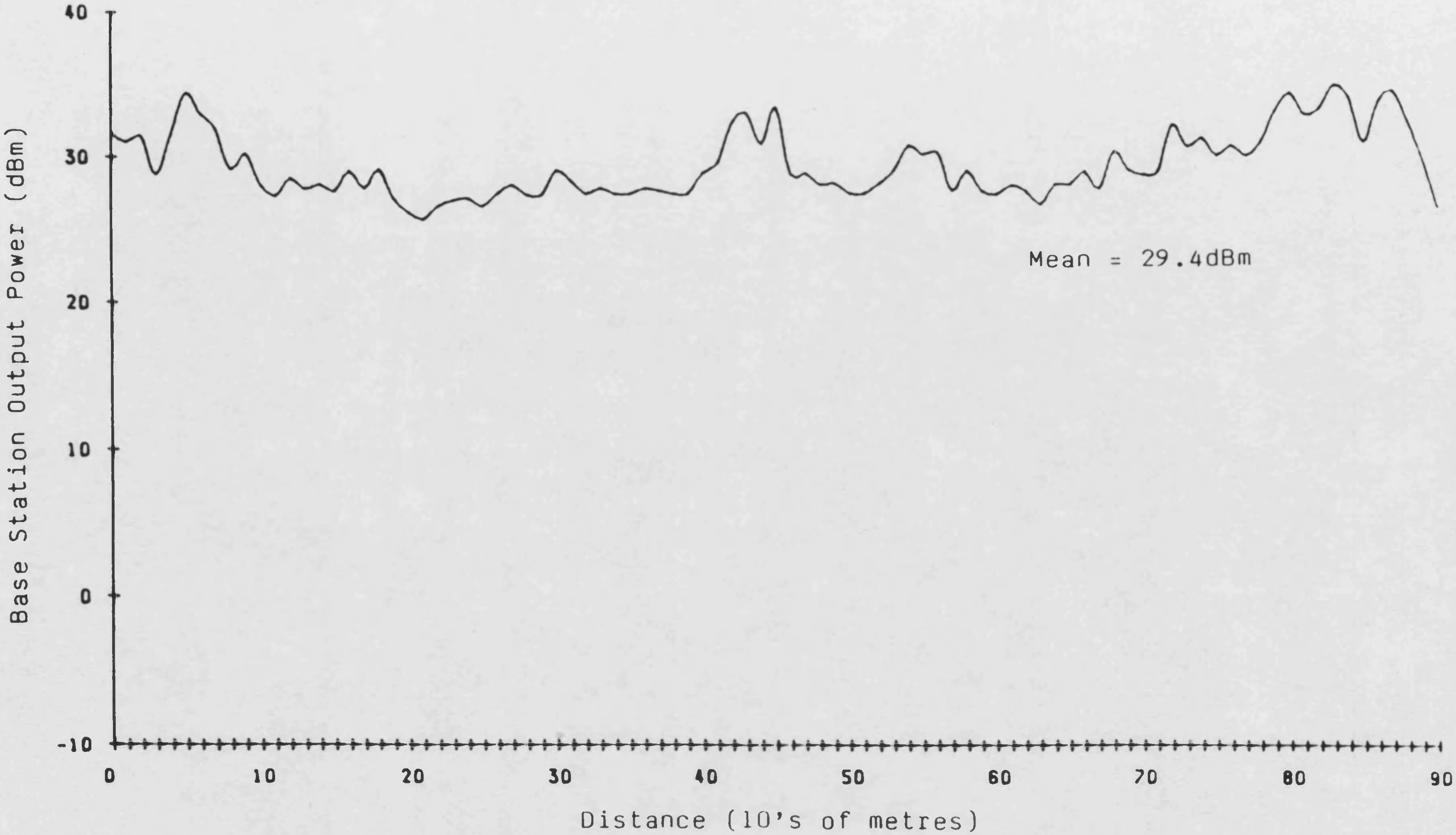


Figure 9.25b. Base Station Output Power for Test Route B at 50mph.

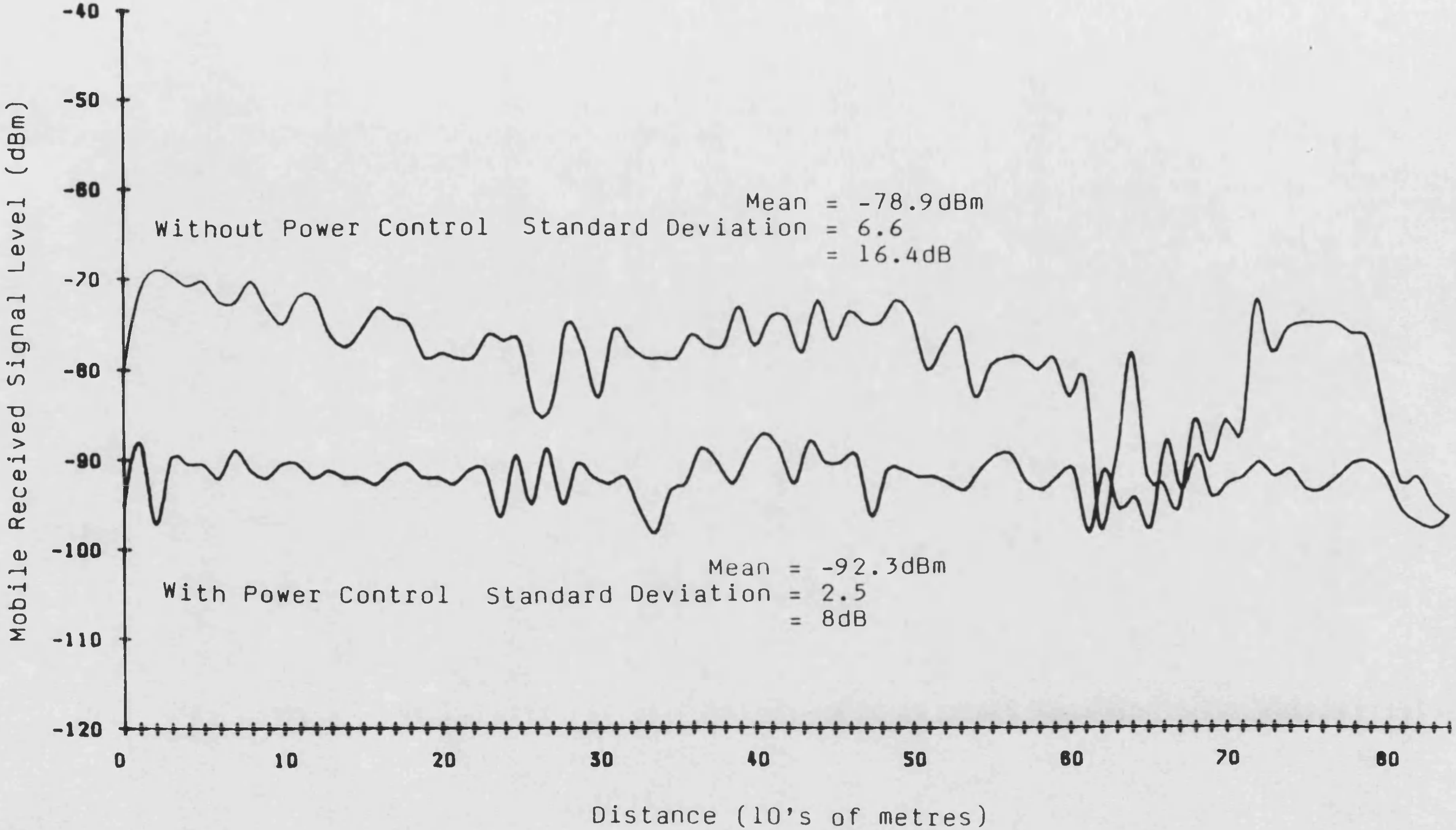


Figure 9.26a. Mobile Received Signal Level for Test Route C at 30mph.

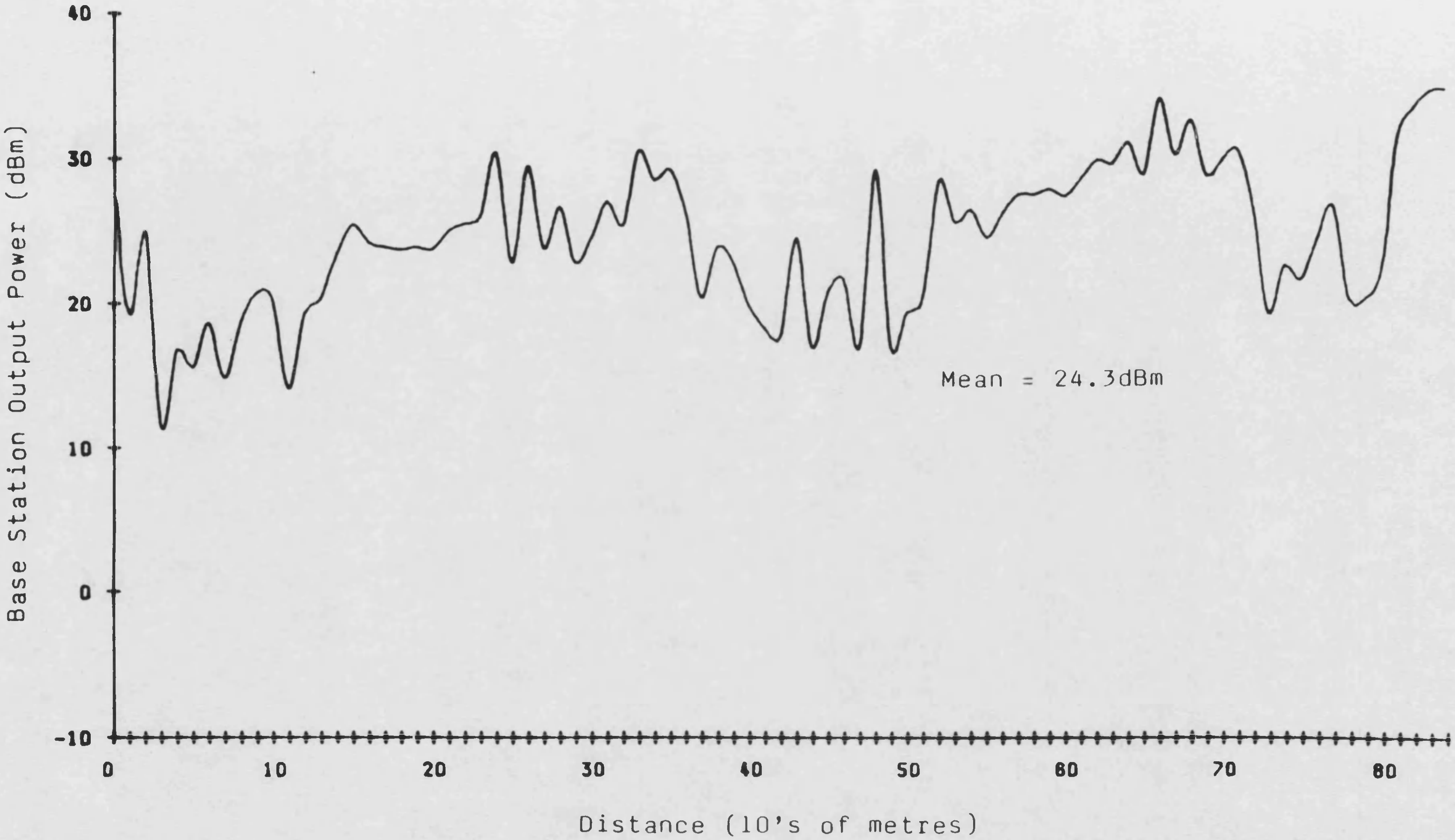


Figure 9.26b. Base Station Output Power for Test Route C at 30mph.

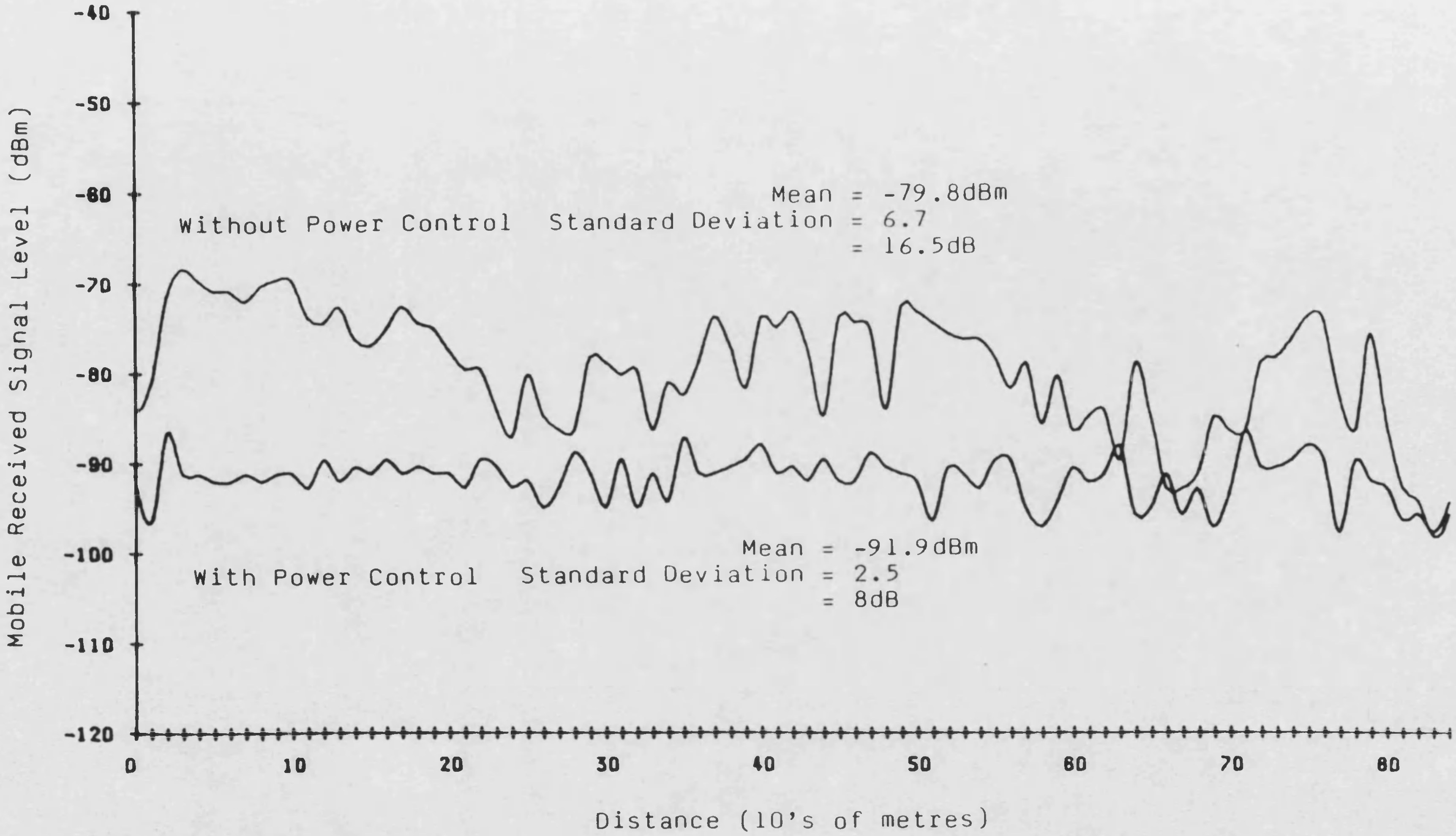


Figure 9.27a. Mobile Received Signal Level for Test Route C at 40mph.

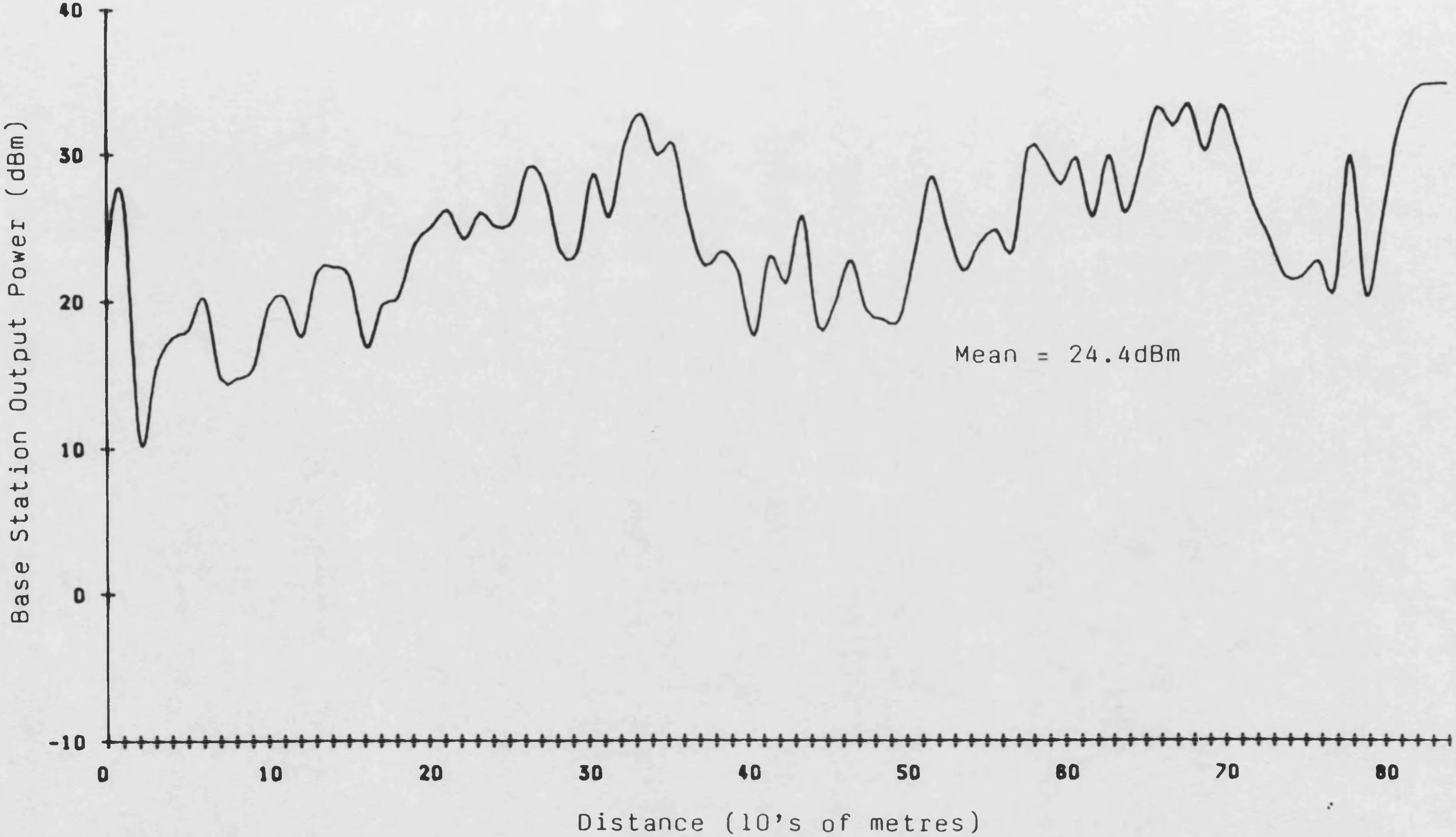


Figure 9.27b. Base Station Output Power for Test Route C at 40mph.

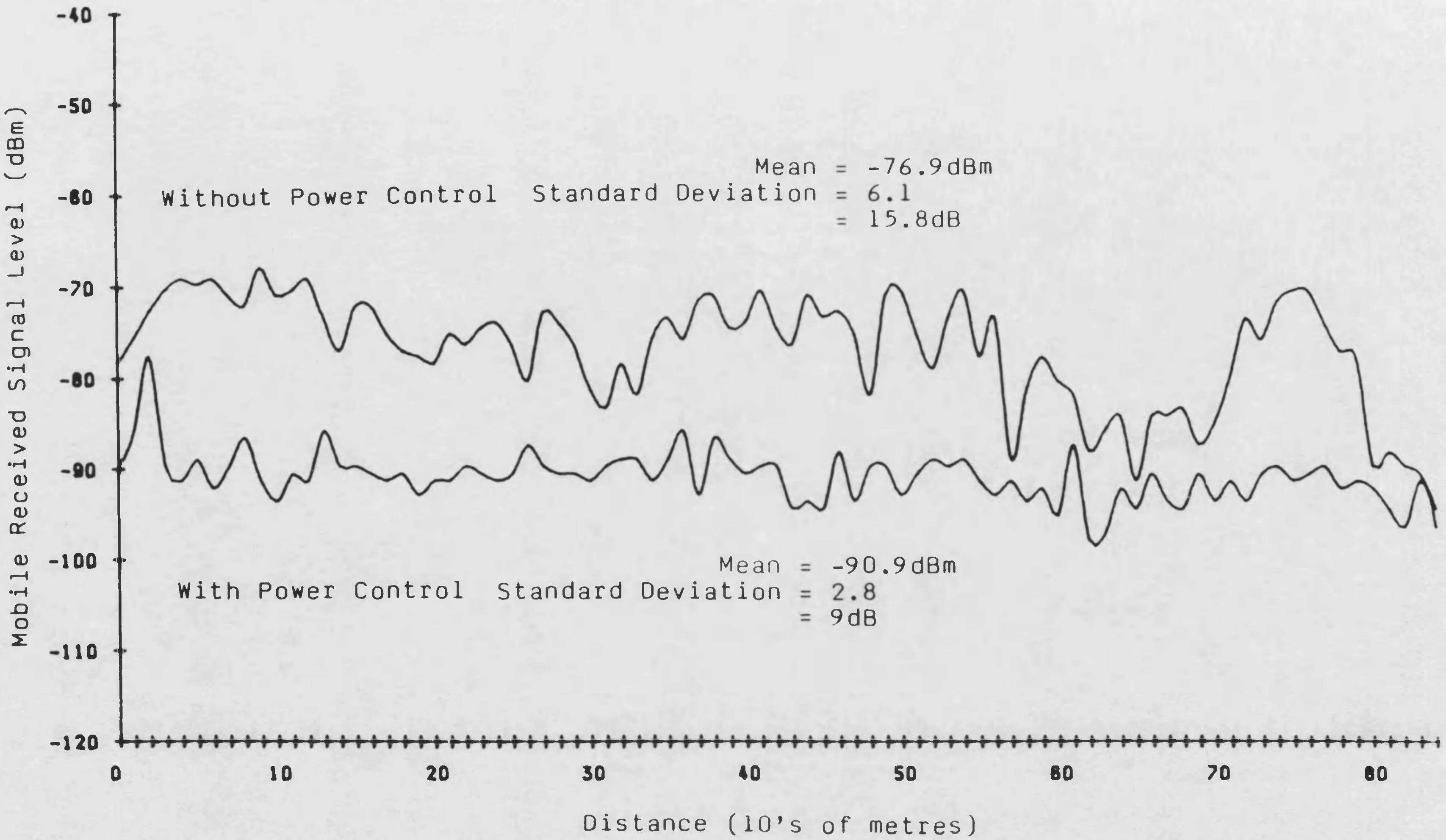


Figure 9.28a. Mobile Received Signal Level for Test Route C at 30mph.

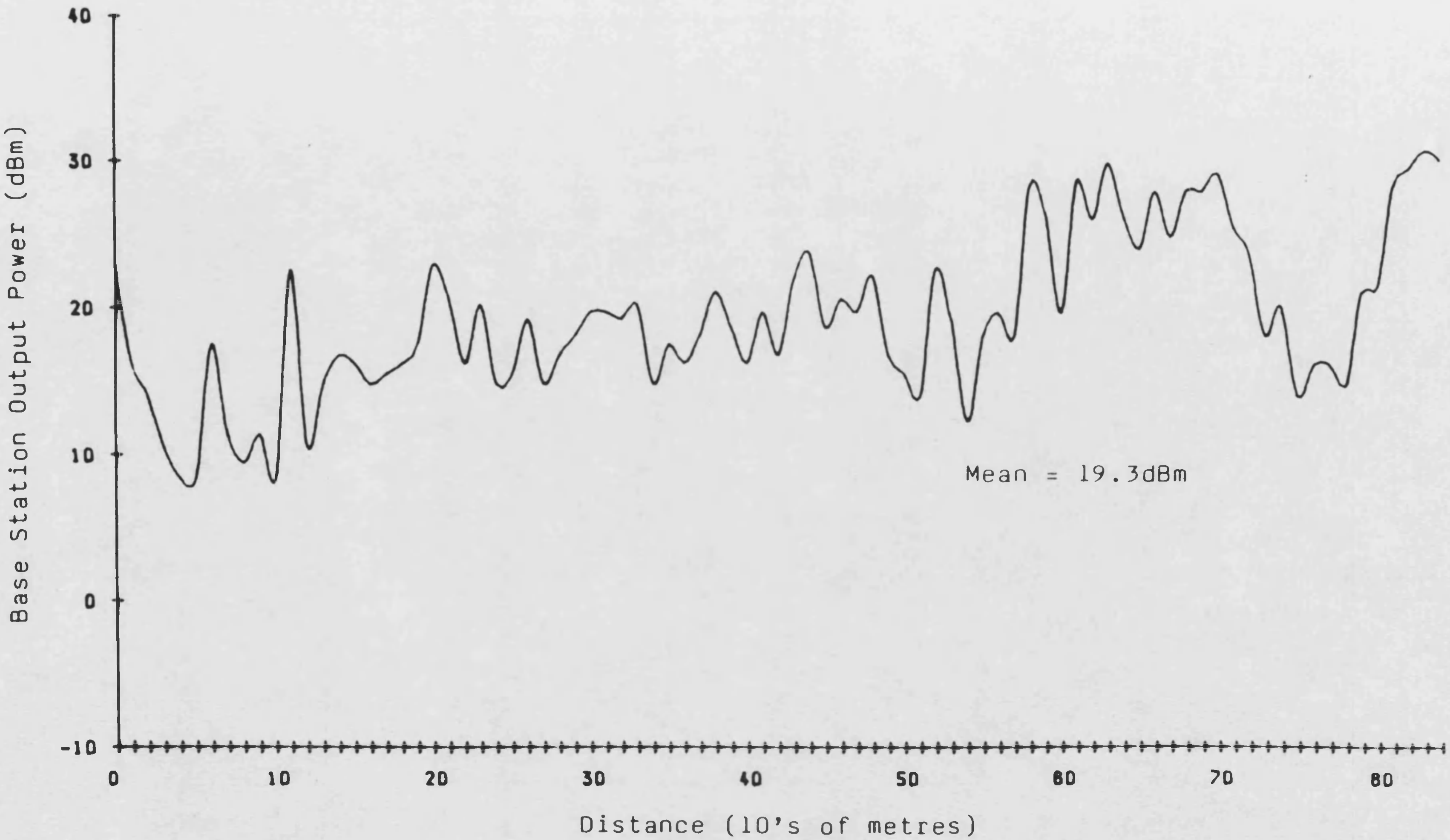


Figure 9.28b. Base Station Output Power for Test Route C at 30mph.

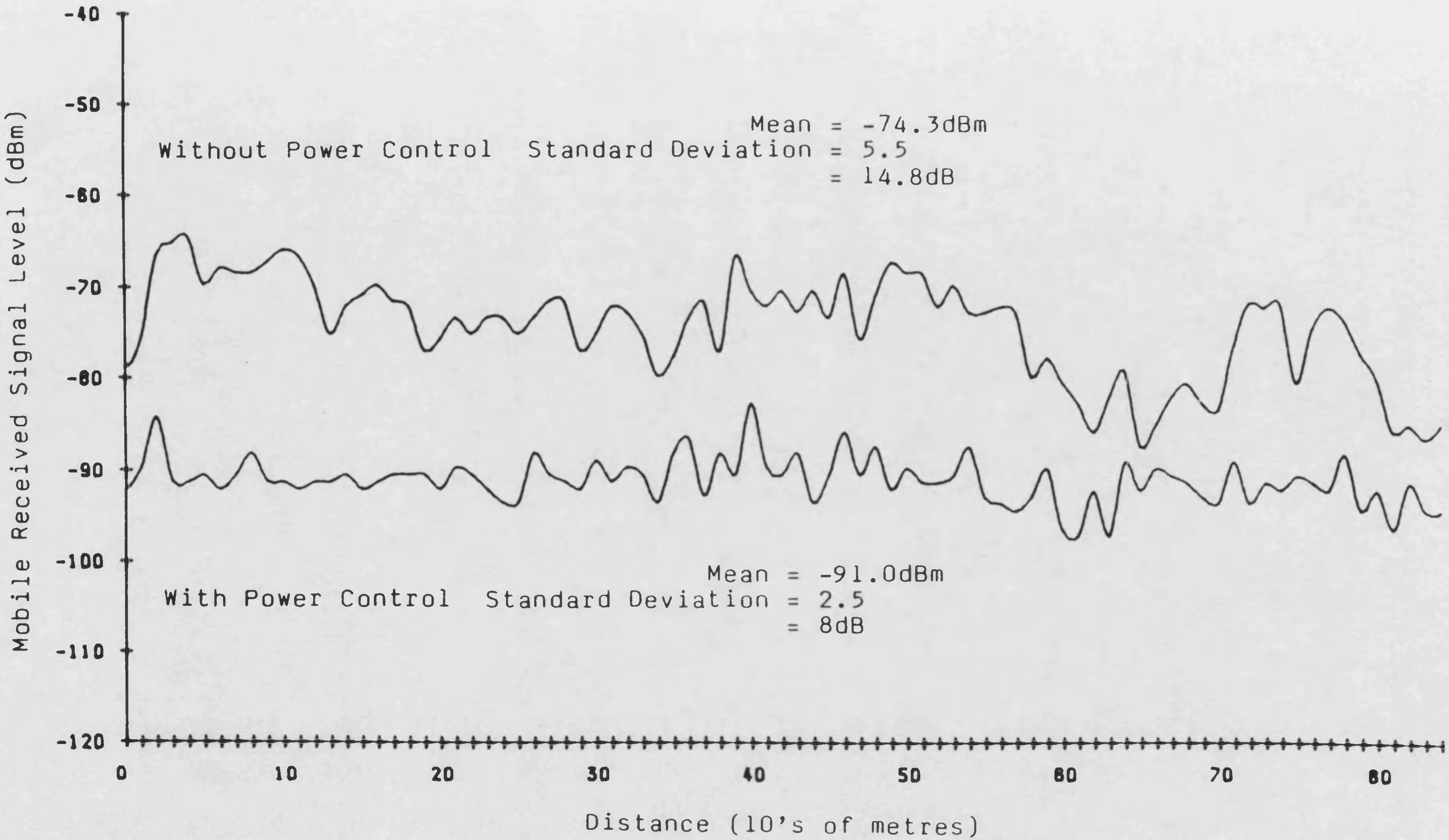


Figure 9.29a. Mobile Received Signal Level for Test Route C at 30mph.

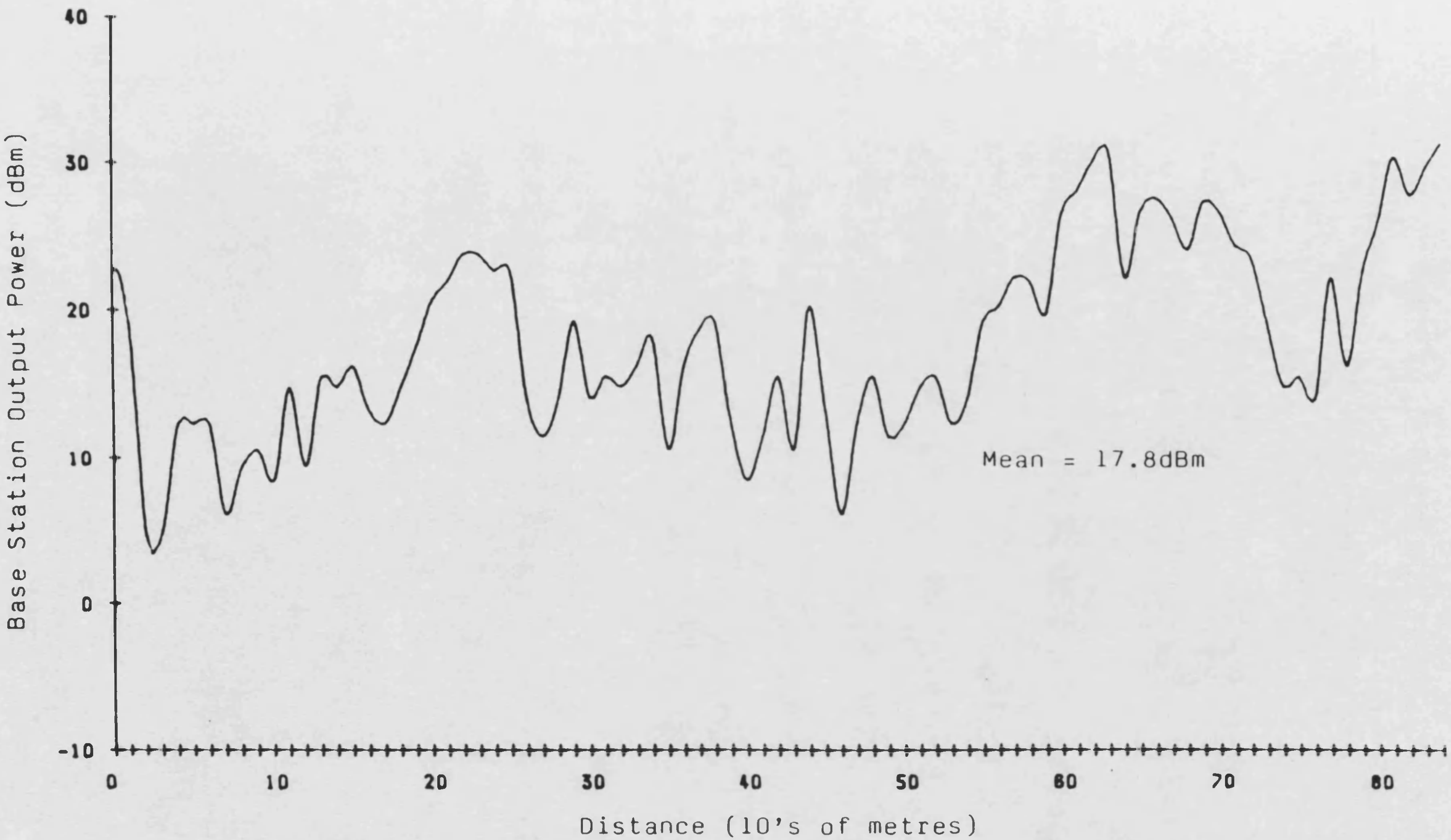


Figure 9.29b. Base Station Output Power for Test Route C at 30mph.

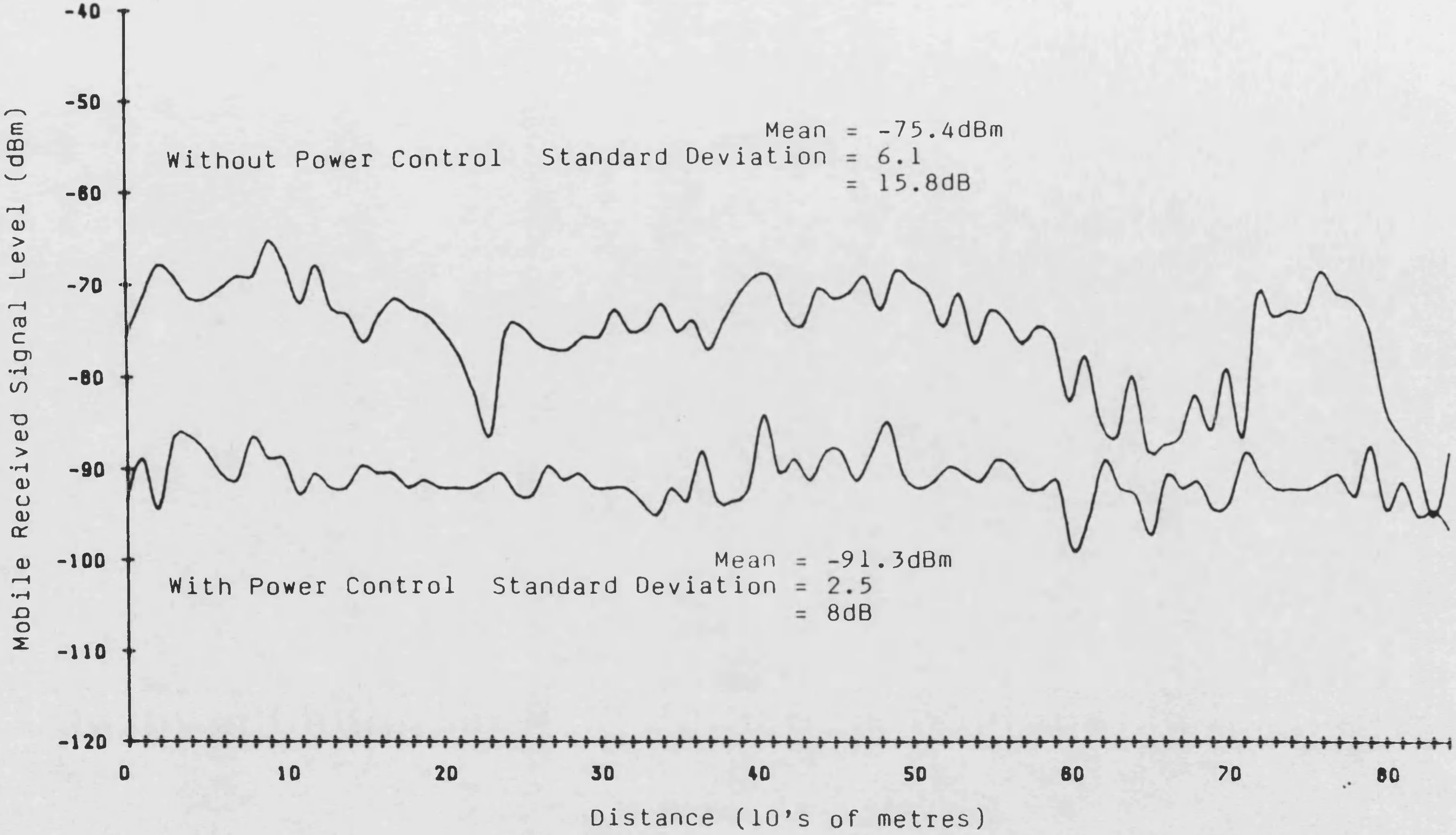


Figure 9.30a. Mobile Received Signal Level for Test Route C at 30mph.

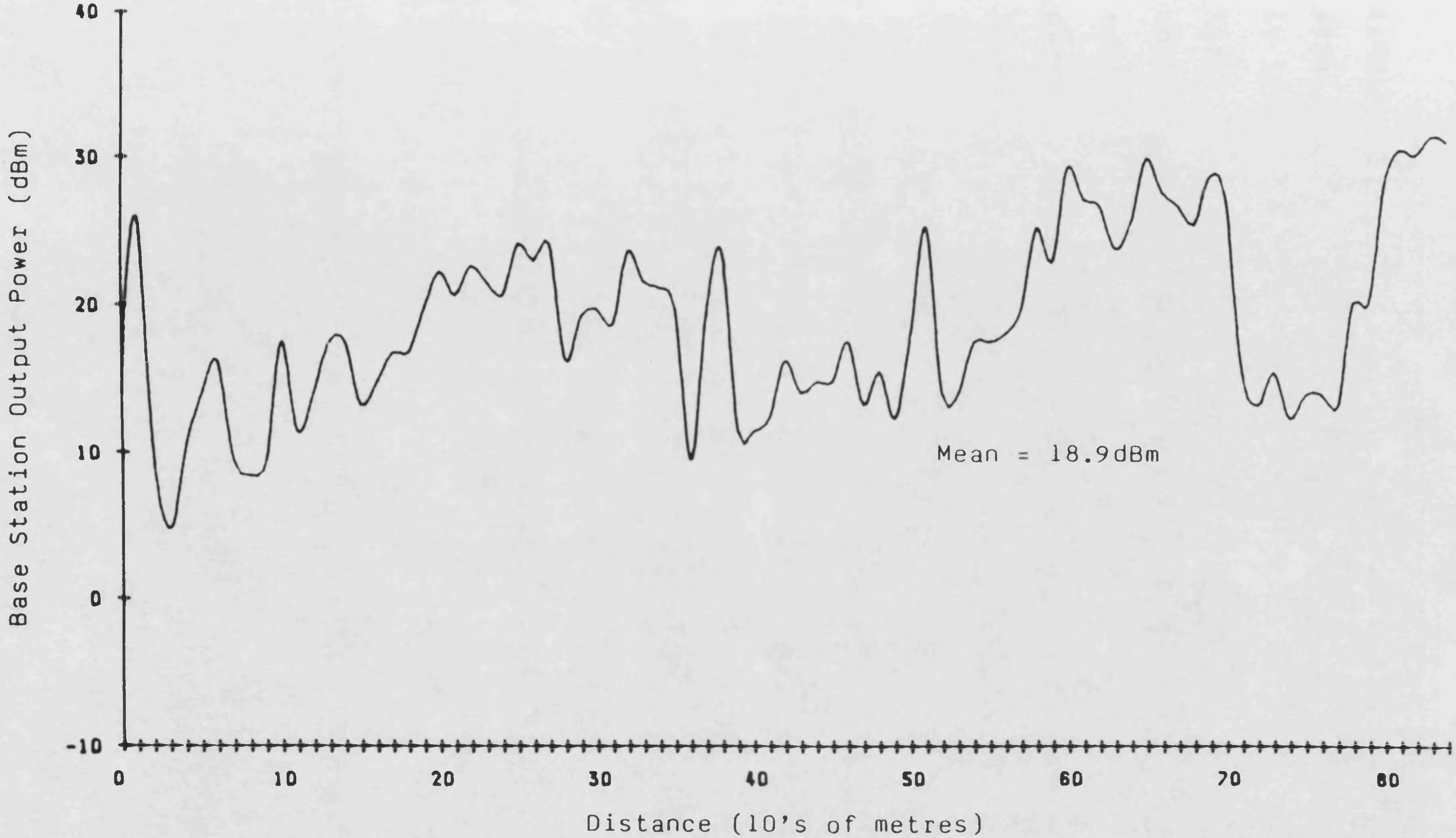


Figure 9.30b. Base Station Output Power for Test Route C at 30mph.

simultaneously but sequentially in time through two separate runs, they contain inherent differences.Thus it is the trends within the results which must be examined in order to assess the performance of the power control system. The reduction in the mean level of the mobile received signal brought about by the use of the power control system can clearly been seen in the measurements taken over all three test routes. A corresponding reduction in the variability of the received mobile signal level due to the use of the base station power control system is also evident, not only visually from the graphs but also from a comparison of the standard deviation values of the two received signal strength characteristics.

The results obtained from the trials performed over the same test route at different vehicle speeds show the power control system to be capable of consistent operation at least up to the maximum test speed of 50mph. Also the close agreement between the results shown in Figures 9.28 to 9.30 obtained from three sets of runs carried out over the same test route at the same speed illustrates the repeatable performance of the power control system.

The difference between the mean received mobile signal level with and without base station power control, as might be expected, closely matches the reduction in the mean level of base station output power gained through the use of power control. The results obtained over the three test routes possess mean base station transmitter power levels that range from approximately 6dB below to as much as 18dB below the maximum output power of 3.5W. A visual comparison of the graphs of base station output power and received mobile signal level without power control for a test route show a high degree of negative correlation between the two as would be expected. However, the non-time synchronous nature of the two sets of results precludes the performance of any meaningful correlation calculations.

The measurements taken over the three test routes show that without power control, the power transmitted from the base station is far in excess of that required by the mobile to provide a perfectly acceptable communication quality. Obviously, the extent to which a base station power control system can go in reducing mean transmitter power levels is dependent on several factors, including the location of the mobile during the call and the maximum output power of the base station transmitter. However, the use of base station power control would always ensure that only the minimum power necessary was being used. As cellular systems become more established and cell sizes are reduced to enable the large volume of traffic that these schemes will inevitably handle, to be accommodated, the ability to perform this close matching of base station power could prove to be invaluable. Also, the requirement of LMR systems in general, to support more and more users could mean that unless further significant allocations of spectrum are made, channel frequencies could eventually have to be re-used at smaller and smaller distances. As cellular systems will undoubtably find out, this can cause severe problems with co-channel interference, and the use of a power control system could well be the only option available in order to reduce the prohibitively high levels to more acceptable proportions.

CHAPTER TEN

CONCLUSIONS

The radio frequency spectrum is a finite resource of which only a small fraction has ever been allocated to the Land Mobile Radio Service. Accommodation of the ever increasing number of users has historically been achieved by progressive reductions in channel bandwidths and the judicious application of frequency re-use.

The advent of 900MHz national cellular radio, and to a lesser extent the licensing of trunked systems in Band III, have modified the radio system designers approach to both co-channel interference and intermodulation interference, since the sources of such interference are now potentially under the control of the overall system. To this end, mobile power control has been successfully applied to reduce the intermodulation effects in base station receiver distribution amplifiers, and hence decrease the levels of generated spurious at cell sites.

At present each transmitter at a cellular base station site generates a constant power output therefore defining the cell size, with different power levels, and hence cell sizes, being employed to accommodate drastically different user densities. This work has been concerned with the effect of dynamically varying base station transmitter power so as to provide only adequate mobile received signal quality well within the desired service area of any cell thus reducing the level of co-channel interference to mobiles in other co-channel cells. This process is directly equivalent to tayloring the cell size of an individual channel to the immediate requirement of the mobile user.

The implementation of a base station power control scheme comprises of three distinct elements. Firstly the assessment of signal quality, secondly the communication of that information to the base station, and thirdly the adjustment of the transmitter power. The range of methods of implementation and their corresponding complexity and predicted performance are described in detail in chapter seven. Clearly, the simplest approach would be one in which reciprocity between mobile and base station were assumed and hence the information already available at the base station for mobile power control utilised to achieve base station power control.

Simulation of a base station power control scheme in chapter five has shown that an average reduction of base station power of some 8.5dB could be achieved without significantly effecting the overall performance of the system. Considering a seven cell scheme, this would achieve a mean reduction of co-channel interference of 16.3dB, and no reason has been discovered during the work to suggest that figures closely approaching this should not be accomplished in practice.

However, the implementation of power control could lead, under adverse interfering conditions, to a condition where a 'power race' situation developed involving the interaction between the mobile power control system and the base station power control system, which would clearly achieve no advantage in terms of communications quality, but would worsen the situation regarding co-channel interference. Therefore, it is obviously necessary to give the most careful and maticulous consideration, most probably involving a sophistication of the system software, to avoid this undesirable 'power race' situation. This deceptively non-trivial situation requires the most careful attention and is recommended as the major aspect of the continuation of this work.

APPENDIX A

COMPUTER PROGRAMS USED FOR CELLULAR CHANNEL ASSIGNMENTS

```
/* This is the program that generates the IM compatible channel sets. It produces
channel assignments that are 2-frequency third order compatible or both 2 and 3-
frequency third order compatible depending on how the program is compiled. */

#include <stdio.h>

#define reject(expr,array) if (((reg=(expr))>0) && (reg <=SIZE)) (array)->data[reg]=1
/* Defines a macro called "reject" which marks the channel numbers that cannot be
assigned due to previously assigned channels. */

struct ARRAY { char data[200+1]; };
struct ARRAY orig;
/* Sets up an array in which to store details of the channels that have been assigned
or those that are barred from assignment on IM grounds. */

int vals[200];
/* Sets up an array in which to store the numbers of the compatible channels - maximum
limit of 200. */

int size;
int separation;
int b;
int c;
/* Declarations of integer variables. */

main()
{
        scanf("%d",&size);
        /* Reads in total number of available channels   maximum of 200. */

        scanf("%d",&separation);
        /* Reads in minimum separation permissible between channels assigned to the
        same base station. */

        scanf("%d",&b);
        /* Reads in the number of channels required per cell. */

        c=(b-1);
        recur(&orig,0,1);
        /* Sets first assigned channel to channel number 1 - first time round only. */

}

recur(olddata,level,startp) register struct ARRAY *olddata; register int level;
/* Defines a function called "recur" which updates the list of channels presently
allocated and those barred from allocation, and keeps track on the number of channels
so far assigned and the channel number at which to start looking for the next possible
assignable channel. */

register int startp;
{
        register int i;
        register int reg;
        struct ARRAY newdata;
        /* Sets up an array to contain details of the channels barred by the assignment
        of the present channel. */
```

```
	for(;startp<=size;startp++)
	{
		if (olddata->data[startp]) continue;
		/* Checks to see if the next channel with the required separation does
		not have any third order relationship with any previously assigned
		channels. */

		vals[level]=startp;
		/* Records the channel number in the list of compatible channels. */

		if (level<c) {
		/* Checks to see if enough channels have already been obtained. */

		newdata= *olddata;
		/* Adds channels barred by the allocation of the latest channel to the
		list of channels already assigned or barred from assignment. */

		for(i=0;i<level;i++){
#ifdef ALL
/* Option used in compiling to obtain complete third order compatibility. */

			register int j;
			for(j=0;j<i;j++){
				reject(vals[i]+vals[j]-startp,&newdata);
				reject(vals[i]-vals[j]+startp,&newdata);
				reject(vals[j]-vals[i]+startp,&newdata);
				/* Checks channel that has just been assigned with all
				previously allocated channels to locate which higher
				number channels cannot be assigned due to 3-frequency
				third order IM product relationship with previosly
				allocated channels. */

				}
#endif
			reject(2*vals[i]-startp,&newdata);
			reject(2*startp-vals[i],&newdata);
			/* As above except for 2 frequency third order relationships. */

			}
		recur(&newdata,level+1,startp+separation);
		/* Returns to find the next compatible channel for the list. */

		}
		else{
			register int k;
			for(k=0;k<=level;k++)
				printf(" %d",vals[k]);
			printf("0);
			/* Prints out list of compatible channel numbers. */

		}
	}
	/* Returns to find the next set of compatible channels. */

}
```

```
/* This is the program that generates the groups of compatible channel sets. This
particular program is for a cell cluster size of nine. */

#include <stdio.h>

int n;
/* Declaration of integer variable. */

unsigned *array;
unsigned *array2;
unsigned *array3;
/* Declares array,array2, and array3 as pointers to unsigned integers; 32 bit long
memory locations. */

char *calloc();
/* Standard C function for allocation of memory. */

main(argc,argv)
/* Argc and argv are input variables from operating system. */

int argc;
/* Defines the number of input arguments. */

char **argv;
/* Sets up an array in which to store input arguments. */

{
register unsigned t;
register unsigned t2;
register unsigned t3;
int l;
int k;
int j;
int i;
int m;
int p;
int q;
int r;
int s;
/* Declarations of registers and integer variables. */

        i=atoi(argv[1]);
        /* Converts first argument into integer. */

        array=(unsigned*)calloc(i,sizeof(unsigned));
        array2=(unsigned*)calloc(i,sizeof(unsigned));
        array3=(unsigned*)calloc(i,sizeof(unsigned));
        /* Allocates memory space to arrays and sets all elements of arrays to zero. */

        if ((array==NULL)||(array2==NULL)||(array3==NULL))
        {
                printf("Not enough memory0);
                exit(1);
        }
        /* Checks to make sure we have enough free memory. */

        readdat(atoi(argv[2]));
        /* Converts second input argument into integer form for "readdat" function. */

        for (i=0;i<n;i++)
        {
         t=array[i];
         t2=array2[i];
         t3=array3[i];
         /* Reads in a set of compatible channel numbers. */

         for (j=i+1;j<n;j++)
```

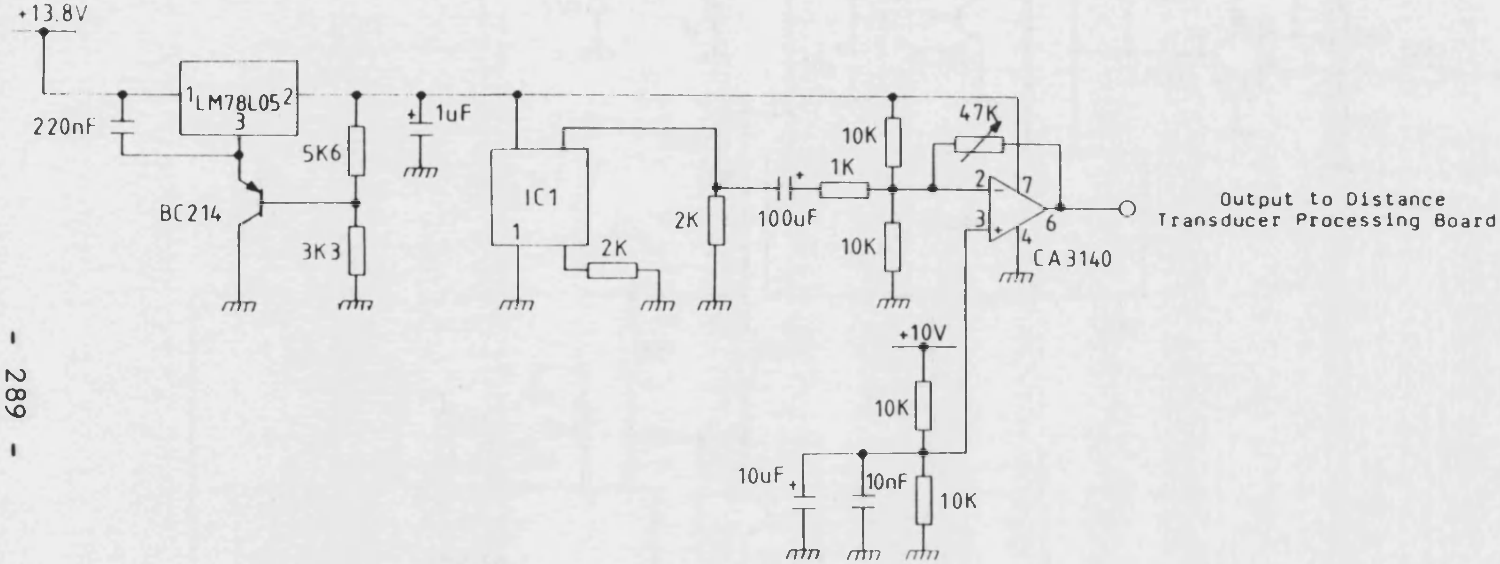
```
{
 if (t & array[j]) continue;
 if (t2 & array2[j]) continue;
 if (t3 & array3[j]) continue;
 /* Reads in the next set of compatible channel numbers and checks to make
 sure there are no repeated channels with the previous set. */

 t += array[j];
 t2 += array2[j];
 t3 += array3[j];
 /* Combines the channel numbers of the previous and present channel sets
 to create a list of channel numbers so far assigned. */

 for (k=j+1;k<n;k++)
 {
  if (t & array[k]) continue;
  if (t2 & array2[k]) continue;
  if (t3 & array3[k]) continue;
  /* Reads in next set of channels and checks with previous sets for channel
  uniqueness. */

  t += array[k];
  t2 += array2[k];
  t3 += array3[k];
  /* Adds channel numbers to list of already assigned channels. */

  for (l=k+1;l<n;l++)
  {
   if (t & array[l]) continue;
   if (t2 & array2[l]) continue;
   if (t3 & array3[l]) continue;
   /* Next set of channels. */

   t += array[l];
   t2 += array2[l];
   t3 += array3[l];
   /* Adds in channel numbers. */

   for (m=l+1;m<n;m++)
   {
    if (t & array[m]) continue;
    if (t2 & array2[m]) continue;
    if (t3 & array3[m]) continue;
    /* Next set of channels. */

    t += array[m];
    t2 += array2[m];
    t3 += array3[m];
    /* Adds in channel numbers. */

    for (p=m+1;p<n;p++)
    {
     if (t & array[p]) continue;
     if (t2 & array2[p]) continue;
     if (t3 & array3[p]) continue;
     /* Next set of channels. */

     t += array[p];
     t2 += array2[p];
     t3 += array3[p];
     /* Adds in channel numbers. */

     for (q=p+1;q<n;q++)
     {
      if (t & array[q]) continue;
      if (t2 & array2[q]) continue;
      if (t3 & array3[q]) continue;
```

```
            /* Next set of channels. */

            t += array[q];
            t2 += array2[q];
            t3 += array3[q];
            /* Adds in channel numbers. */

            for (r=q+1;r<n;r++)
            {
             if (t & array[r]) continue;
             if (t2 & array2[r]) continue;
             if (t3 & array3[r]) continue;
             /* Next set of channels. */

             t += array[r];
             t2 += array2[r];
             t3 += array3[r];
             /* Adds in channel numbers. */

             for (s=r+1;s<n;s++)
             {
              if (t & array[s]) continue;
              if (t2 & array2[s]) continue;
              if (t3 & array3[s]) continue;
              /* Next set of channels. */

              setout(argv[3]);
              /* Opens output file with desired filename if solution is found. */

              printf("%3d %3d %3d %3d %3d %3d %3d %3d %3d0,i,j,k,l,m,p,q,r,s);
              printf("There is at least one solution0);
              /* Prints out the first group of IM compatible channel sets. */

              goto end;
              /* Program stops. */

             }
             t &= ~ array[r];
             t2 &= ~ array2[r];
             t3 &= ~ array3[r];
             /* Removes channel numbers added by the inclusion of channel set "r"
             from the list of the channels so far allocated. */

            }
            t &= ~ array[q];
            t2 &= ~ array2[q];
            t3 &= ~ array3[q];
            /* Removes channel numbers added by the inclusion of channel set "q"
            from the list of the channels so far allocated. */

           }
           t &= ~ array[p];
           t2 &= ~ array2[p];
           t3 &= ~ array3[p];
           /* Removes channel numbers added by the inclusion of channel set "p"
           from the list of the channels so far allocated. */

          }
          t &= ~ array[m];
          t2 &= ~ array2[m];
          t3 &= ~ array3[m];
          /* Removes channel numbers added by the inclusion of channel set "m"
          from the list of the channels so far allocated. */

         }
         t &= ~ array[l];
         t2 &= ~ array2[l];
```

```
t3 &= ~ array3[l];
/* Removes channel numbers added by the inclusion of channel set "l"
from the list of the channels so far allocated. */

}
t &= ~ array[k];
t2 &= ~ array2[k];
t3 &= ~ array3[k];
/* Removes channel numbers added by the inclusion of channel set "k"
from the list of the channels so far allocated. */

}
t &= ~ array[j];
t2 &= ~ array2[j];
t3 &= ~ array3[j];
/* Removes channel numbers added by the inclusion of channel set "j"
from the list of the channels so far allocated. */

}
t &= ~ array[i];
t2 &= ~ array2[i];
t3 &= ~ array3[i];
/* Removes channel numbers added by the inclusion of channel set "i"
from the list of the channels so far allocated. */

}
setout(argv[3]);
/* Opens output file with desired filename. */

printf("There is no solution0);
end: printf("End of program0);
/* No solution to the problem. */

}

readdat(c)
/* Defines a function called "readdat". */

{
int i,j;
        for (n=0;;n++)
        /* Counts the number IM compatible channel lists that we have. */

        {
                for (i=0;i<c;i++)
                /* Reads compatible lists into arrays. */

                {
                        if (scanf("%d",&j)!=1) return;
                        /* End of file indicator. */

                        if (j>64) array3[n]+= (1<<(j-65));
                        else if (j>32) array2[n]+= (1<<(j-33));
                        else array[n] +=(1<<(j-1));
                        /* Reads compatible channel numbers into the correct arrays. */

                }
        }
}

setout(s)
char *s;
{
        freopen(s,"w",stdout);
}
/* Function that automatically opens output file when a solution is obtained. */
```

APPENDIX B

HARDWARE USED IN TESTING AND EVALUATION OF POWER CONTROL SYSTEM



IC1 - RS Part No. 304-267 - Hall Effect IC Mounted Directly on Rear of Test Vehicle Speedometer

Figure B.1. Distance Transducer.

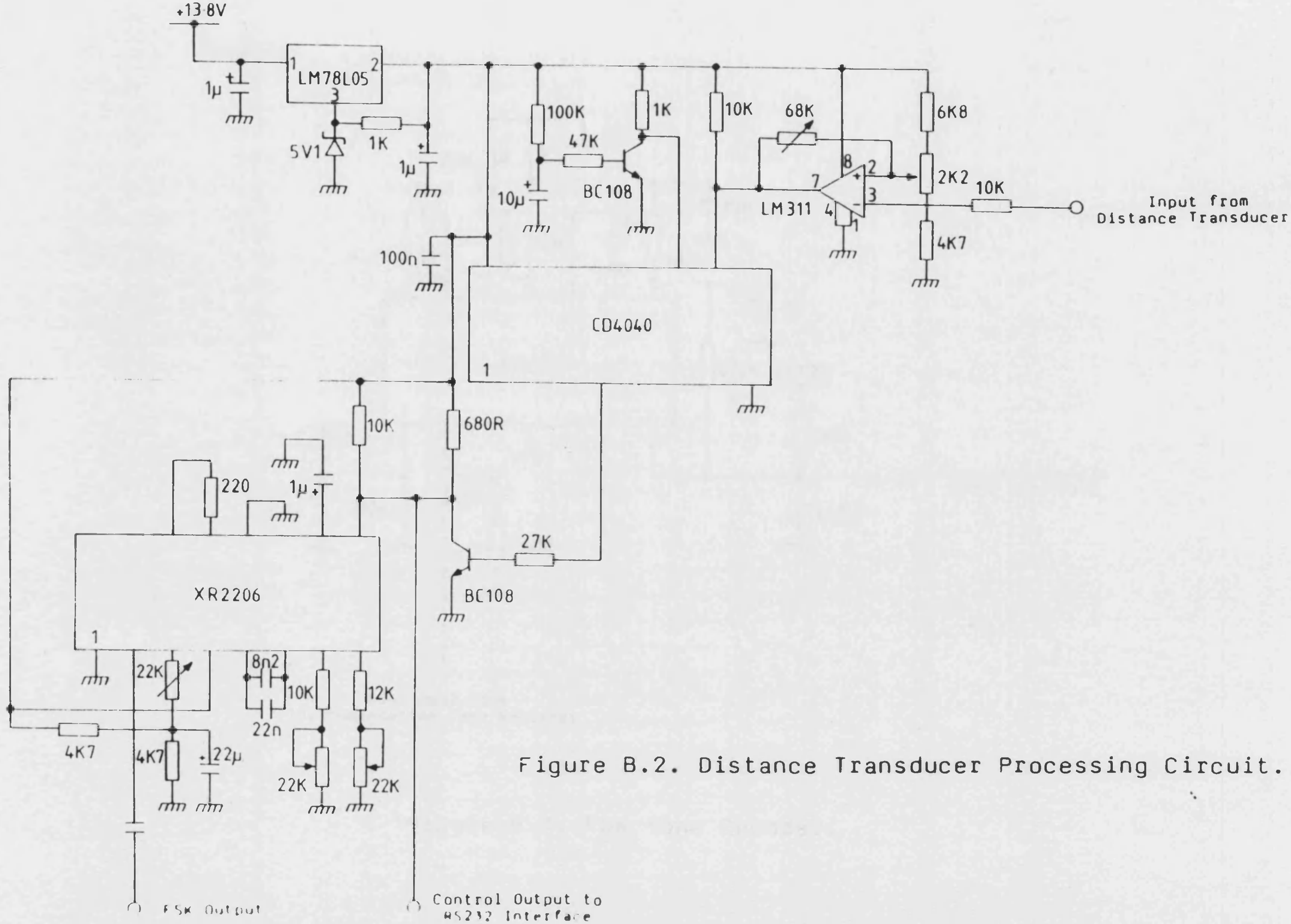


Figure B.2. Distance Transducer Processing Circuit.

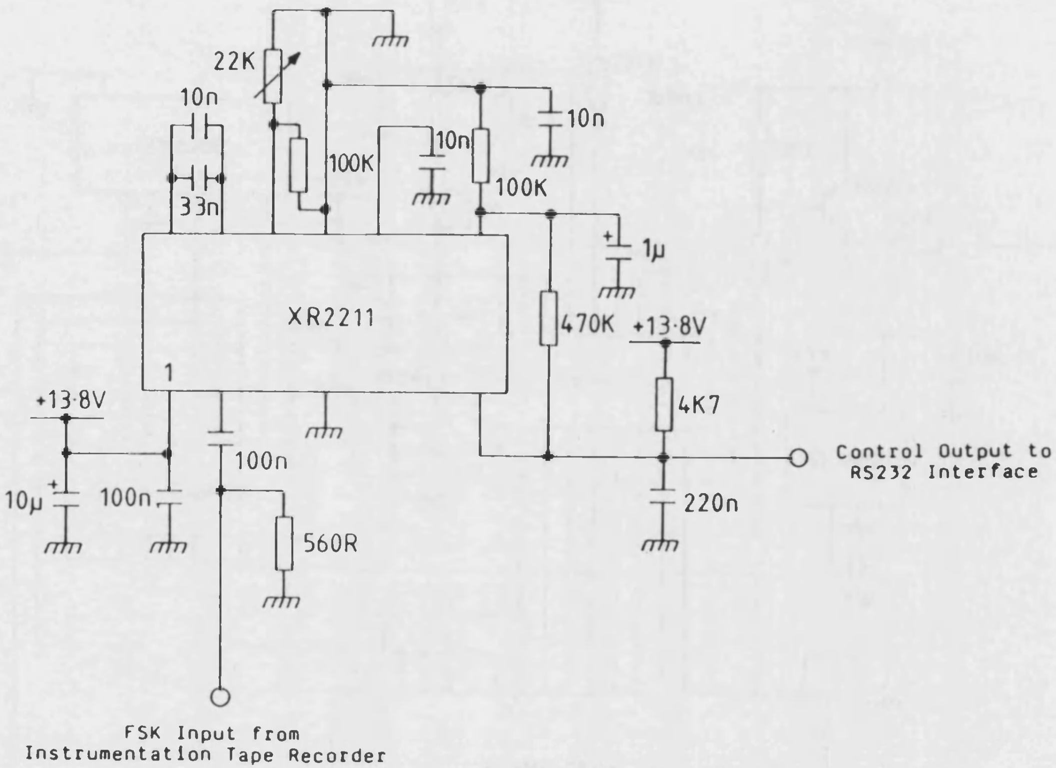


Figure B.3. FSK Tone Decoder.

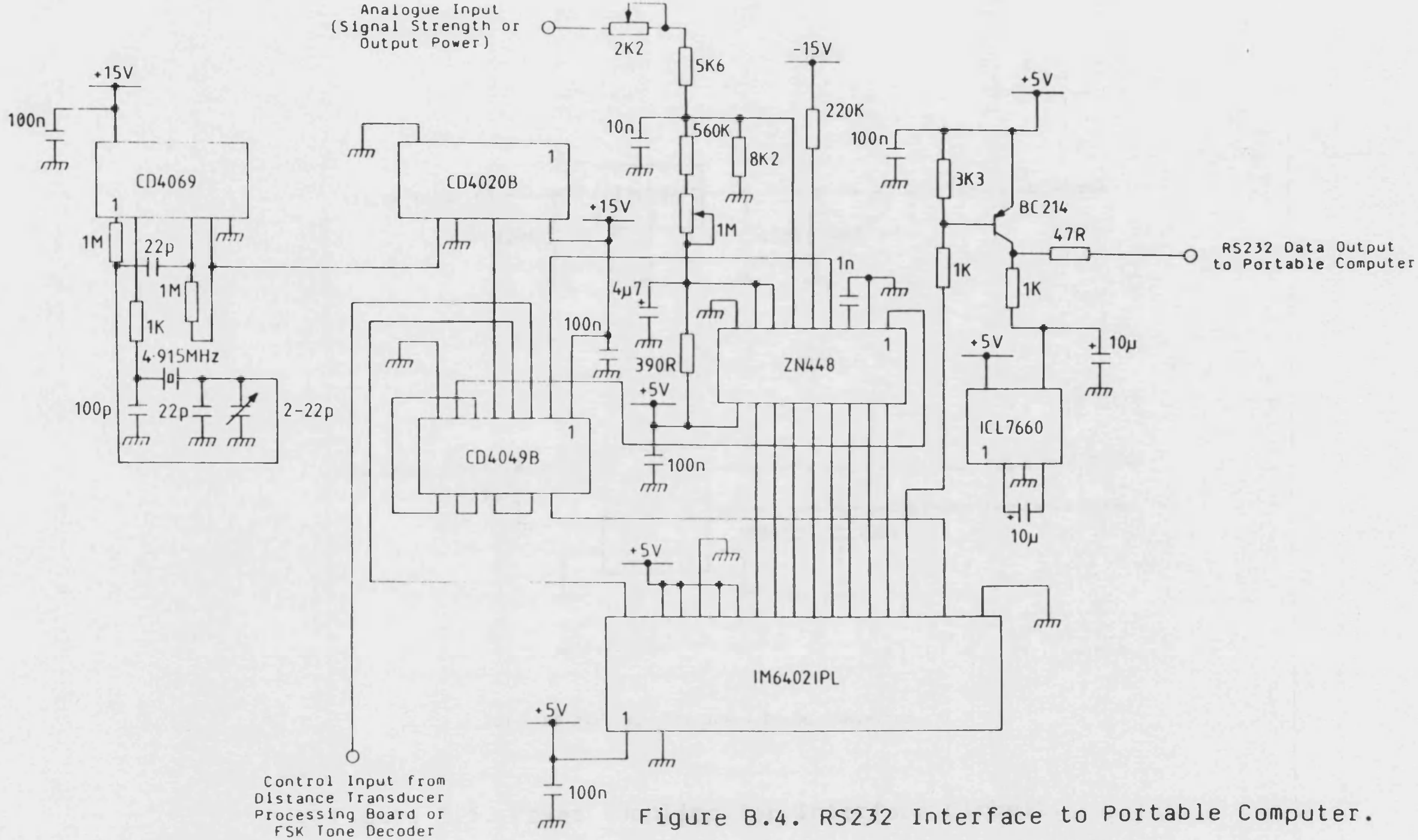
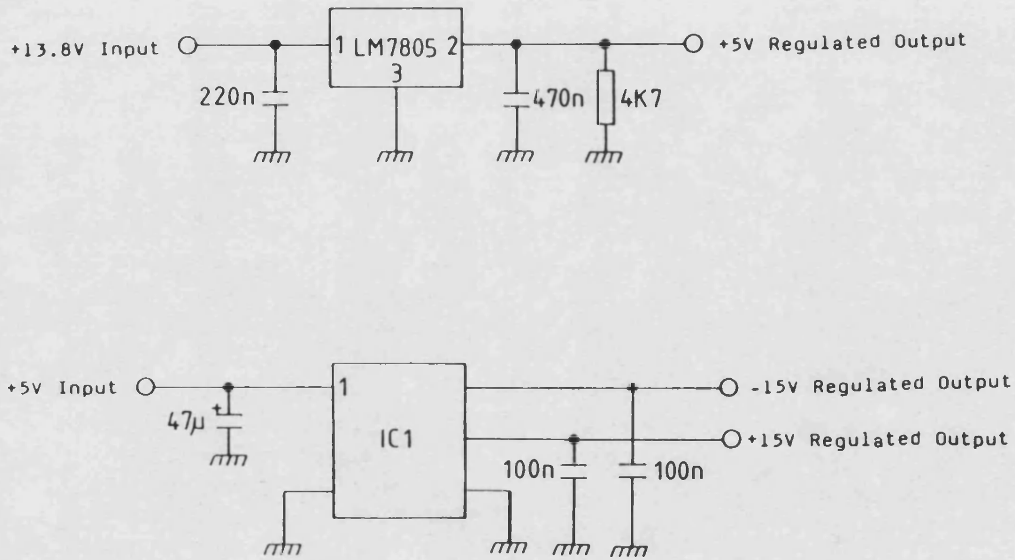


Figure B.4. RS232 Interface to Portable Computer.



IC1 - RS Part No. 591-304 - DC-DC Converter

Figure B.5. Power Supplies for Interface Circuit.

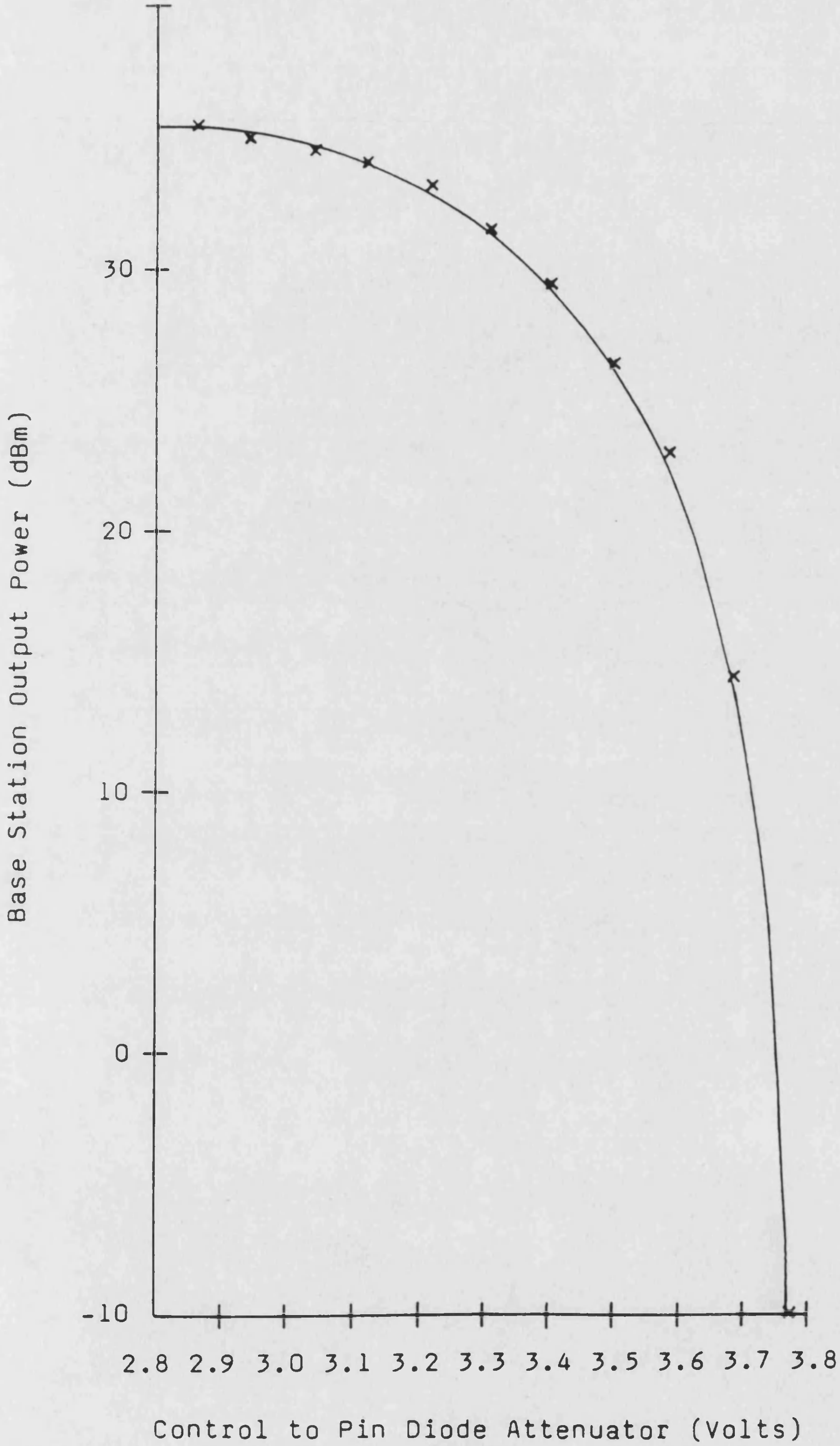


Figure B.6. Base Station Transmitter Characteristic Used for Output Power Determination.